Flowmetering Current Practice
&
Uncertainty Case Studies

A Report for

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Dept of Trade & Industry, London

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EXECUTIVE SUMMARY

The National Engineering Laboratory (NEL) has been contracted to undertake a study into the issues which can affect the quality of flow data and to consider data analysis techniques which can be used to indicate flowmeter performance. The funding for this work was provided by joint contributions from the UK's Department of Trade and Industry through the NMSPU (National Measurement System Policy Unit) 1999-2002 Flow Programme, together with co-funding from a number of UK water companies: Anglian Water, Dwr Cymru, Northumbrian Water, Southern Water, Thames Water and Yorkshire Water.

The open dialogue between the participating members provided a useful opportunity for the sharing and discussion of experiences relating to flow measurement practices. At the beginning of this project a survey was undertaken in order to establish an understanding of current practice in the water industry with regard to flow measurement and this work is detailed in Appendix A. This survey has highlighted that practices can vary quite considerably from company to company. In addition, the drive for improved flow measurement being demanded by regulatory bodies such as OfWat and the Environment Agency is discussed. It is generally agreed that these bodies do provide the driver for improving flow measurement. However, it is interesting to see how the various companies have prioritised their finite resources in different areas. Some companies have concentrated efforts in water into supply metering whilst others have concentrated on abstraction metering. Having said this, with continued effort and time, the water companies are generally making substantial improvements in both these areas.

Whenever the quality (or accuracy) of data is discussed, in this case flowmetering data, a fundamental concept which goes hand in hand with this, is uncertainty. It has to be recognised that a reported flow result is only an estimate of the true value, and there has to exist an element of doubt in how close the flow measurement is to the truth. Since both regulators and managers need to know the accuracy of reported results, in order to make informed decisions about operational and management issues, an appreciation of the application of uncertainty analysis techniques is necessary. A methodology which gives guidance on how to evaluate the uncertainty of a measurement, and which has received international acceptance, is provided in Appendix B.

Uncertainty analysis is often perceived by those unaccustomed to the discipline as notoriously abstract, complicated, and laborious. The best way, in such circumstances, to demonstrate the merits and applicability of the methodology is by way of example. For this reason an uncertainty analysis example is provided in Appendix C which follows the methodology provided in Appendix B and examines a particular water industry related problem. Here, in the hypothetical scenario, it is discovered that the mass balance at a water treatment works does not balance. The difference between the abstraction input into the system and the water into supply exiting the site does not equate to the internal water usage on the site which is exited to a pond via a weir. The uncertainty analysis of this system examines whether this imbalance is a result of leakage at the site or whether the imbalance can be accounted for in the uncertainty of the measurements.

In order to maintain a focus on issues of particular industrial relevance to the water industry it was agreed at the outset of the project that a number of case studies would be investigated. These studies, which are provided in Appendices D to H,

formed separate and discreet packages of work and contributed to the overall project aims of addressing data quality and data analysis techniques.

A very broad range of topics was addressed in these five case studies from issues related to the uncertainty of meter verifications using insertion probes and clamp-on ultrasonic meters to the assessment of the flow data signal path from the meter, through telemetry, to the data viewed by the users on their computers in the office. The last of the case studies investigated a number of flow-related data files provided by one of the participants.

Overall, this report provides the UK water industry with an objective account of current flowmetering practices and details the methodology, together with a worked example, to demonstrate the merits and applicability of uncertainty analysis techniques. The various case study reports serve to provide details of the uncertainties associated with certain flow measurement practices and give recommendations for improved operating procedures. More specifically, the case studies provide benefits to industry in three key areas: (1) allows informed decisions to be made regarding the use of verification instruments and operating procedures, particularly with insertion probe and ultrasonic clamp-on technologies, (2) identifies and describes the potential for data signal deterioration throughout the signal path, and (3) provides a number of data analysis techniques that will help the water industry make more effective use of the flow data that they are collecting.

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1 INTRODUCTION

Water companies in the UK, and elsewhere, are investing a great deal of time, effort and resources in flowmetering and data logging technologies. In order to achieve the best return from this investment it is of paramount importance that the flow data being recorded is accurate and therefore truly representative of the actual flows.

The National Engineering Laboratory (NEL) has been contracted to undertake a study into the issues which can affect the quality of flow data and to consider data analysis techniques which can be used to indicate flowmeter performance.

The funding for this work was provided by joint contributions from the UK's Department of Trade and Industry through the NMSPU (National Measurement System Policy Unit) 1999-2002 Flow Programme, together with co-funding from a number of UK water companies: Anglian Water, Dwr Cymru, Northumbrian Water, Southern Water, Thames Water and Yorkshire Water.

2 OVERVIEW OF REPORT

2.1 Project Steering

The major advantage from having genuine commitment, interest and participation from the various water companies involved in this project was the direction and support they provided. Regular steering committee meetings were held with the water company representatives, together with DTI, throughout the course of the project. This ensured that the work was carried out with a focus on issues of particular industrial relevance. These meetings were held once a quarter and were timed to coincide with the WINDFAL (Water Industry Flow Advisory Liaison Group) meetings. WINDFAL is a water industry focus group which provides a forum for all flow measurement and flow related issues within the industry. The purpose of the Group is to identify, prioritise and solve common flow related problems and is backed with DTI funding. Throughout the course of this project regular updates on progress were made to the WINDFAL Group. The home page for WINDFAL can be found at: www.windfal.co.uk.

2.2 Layout of this Report

In the early stages of the project it became clear that this report would be made up of a collection of a number of separate and discreet packages of work. These works all contribute to the overall project aim where data quality and data analysis techniques are being addressed.

Each of these packages of work have been prepared in the form of an Appendix and, as such, form stand-alone sections which can be read without the need for detailed study of the entire report.

In the remainder of this section an overview of the various appendices is provided.

2.3 Survey of Water Companies Flow Measurement Practices – Appendix A

The WINDFAL and project steering committee meetings are regarded by the project members to have provided an excellent opportunity for open dialogue. Resulting from this communication was the realisation that flow measurement practices could vary quite considerably between the various water companies.

The first part of this project, which was agreed among the members, was for NEL to undertake a survey of a number of the different companies in order to investigate current practice in the water industry with regards to flowmetering. The findings from this survey are provided in Appendix A.

2.4 Uncertainty Methodology – Appendix B

Fundamental to the assessment of the accuracy of a measurement, (in this case flow measurement), are issues related to uncertainty. It was therefore agreed that a very useful inclusion in the final project report would be a section giving general guidance on the assessment of flow measurement uncertainties. Such a section is included in Appendix B.

2.5 Example of Uncertainty Analysis – Appendix C

For those unaccustomed to uncertainty analysis it is appreciated that the methodology may appear complex, laborious and rather abstract. In order to address this, and to try to make uncertainty analysis more practicable, an uncertainty analysis example is included in Appendix C. In this hypothetical scenario, the mass balance at a Water Treatment Works is examined in order to investigate an apparent imbalance in the system. Here, an uncertainty analysis is performed in order to discover whether the imbalance is likely to be a result of leakage at the site or whether the imbalance could be accounted for in the uncertainty of the measurements.

2.6 Case Studies

In order to maintain a focus on issues of particular relevance to the water industry, it was agreed at the outset of the project that a number of individual case studies should be investigated. All the water company representatives were asked to put forward suggestions which they considered relevant and of particular value to the project. Following discussions with the various parties a number of suggestions were chosen and these particular case studies carried out.

The case study reports, which are provided in Appendices D to H, are briefly described in the following.

2.6.1 Uncertainties Associated With Insertion Probes - Appendix D

Insertion probes (insertion flowmeters) are widely used in industry as a means of measuring flowrate and have a major disadvantage over full bore meters in that they can only provide a flowrate based on a single point velocity measurement. In order to obtain the flowrate through the pipe the probe has to be inserted to various depths across a diameter and measurements of velocity made at each point. The data generated defines the velocity profile and this is integrated to provide the required mean flowrate solution. The accurate determination of mean flowrate using insertion probes is therefore appreciated as not being a trivial exercise and this case study report (Appendix D) aims to identify and describe the various factors that contribute to the uncertainty associated with their application. This information will allow informed decisions to be made regarding both the application of the measuring instrument itself and operating procedures.

Also detailed in this case study report are a number of investigations which have been performed in order to quantify the extent to which various factors affect the probe measurement readings. These investigations include: a comparison of velocity measurements made in a severely distorted profile using a single point measurement and traverse-based measurements, probe mis-alignment effects, and uncertainties introduced by the method-of-cubics integration formula.

2.6.2 An Investigation into the Probe Profiling Technique at a Specific Installation - Appendix E

One of the water companies involved in this project uses insertion probes extensively as a means of verifying the performance of their full bore meters. Their experience with this technology is generally very good and they consider the probe traversing technique as a reliable and repeatable method of meter verification.

However, at a number of their sites with a particular type of installation, such meter verifications using probes were failing to meet expectations. The purpose of this case study (Appendix E) was to examine one such installation and determine the reasons why there is a difficulty verifying the meter to the required level.

2.6.3 Uncertainty Analysis of Clamp-on Ultrasonic Flowmeters - Appendix F

This case study report (Appendix F) identifies and describes the sources of uncertainty that are associated with the application of clamp-on ultrasonic flowmeters. Furthermore, these uncertainties are quantified using theoretical techniques and where possible are backed up with reference to experimental results. This information will aid the industrial users in allowing informed decisions to be made regarding both the use of the measuring instrument itself and operating procedures.

A number of key uncertainty sources are described in detail, including: pipe material and dimensional details, transducer attachment effects, transit time and transit time difference measurements, and velocity profile variations due to installation effects.

2.6.4 Errors in the Data Path from Meter Through to Telemetry - Appendix G

Regulatory bodies in the UK such as the Environment Agency and OFWAT have demanded that the water companies rise to the challenge of improving their flow measurement. In general, the water companies have been steadily improving their flow measurement systems and procedures to meet this challenge and it is now common for them to have in place various systems for verifying the performance of their flowmetering devices. These include the use of secondary metering devices such as clamp-on ultrasonics and insertion probes as well as the application of meter manufacturer's diagnostic verification tools. The main focus during such verifications is to check the performance of the flow measurement device. It is recognised, however, that the electronic flow signal being generated by the meter (typically mA) has be converted into meaningful flowrate information (litres/second). The work presented in this case study (Appendix G) reports on the measurements made during a number of site visits to separate installations and identifies and quantifies the errors that can be introduced into the data path once the flow signal has been generated.

2.6.5 Analysis of Data From Water Meters - Appendix H

The UK water industry is currently making significant investments in new flow metering and data logging technology. As a result large quantities of flow data can now be collected, but if these data are to be used to best advantage the industry must identify effective methods of data analysis. This case study (Appendix H) reports the results of an examination of a number of typical flowmetering data sets. Resulting from these investigations are a number of data analysis techniques that will increase the value to the industry of their investment in new technology.

3 CONCLUSIONS

Overall, this report provides the UK water industry with an objective account of current practices with regards to flowmetering and details the methodology, together with a worked example, to demonstrate the merits and applicability of uncertainty analysis techniques. The report also includes the various case study reports which serve to provide details of the uncertainties associated with certain flow measurement practices and gives recommendations for improved operating procedures. More specifically, these case studies provide benefits to industry in three key areas: (1) allowing informed decisions to be made regarding the use of verification instruments and operating procedures, particularly with insertion probe and ultrasonic clamp-on technologies, (2) identifies and describes the potential for data signal deterioration throughout the signal path, and (3) provides a number of data analysis techniques that will help the water industry make more effective use of the flow data that they are collecting.

APPENDIX A

CURRENT PRACTICE IN THE WATER INDUSTRY WITH REGARDS TO FLOWMETERING

APPENDIX A –

CURRENT PRACTICE IN THE WATER INDUSTRY WITH REGARDS TO FLOWMETERING

A.1 INTRODUCTION

The National Engineering Laboratory (NEL) is currently undertaking a study into the 'Analysis of Data from Water Meters to Determine Performance Indicators'. This is a tendered project that NEL won as part of the Department of Trade and Industry's Flow Programme (1999 – 2002) for the National Measurement System Policy Unit. The project is also supported by the following water companies: Anglian Water, Dwr Cymru (Welsh Water), Northumbrian Water, Southern Water, Thames Water, and Yorkshire Water. Company representatives together with DTI form the steering group for the project. The project was started in April 2000 when the first of four steering group meetings was held.

It was agreed with these members[1] that a useful starting point in this project would be to undertake a survey of the individual water companies to ascertain current practice with regards to flowmetering. In aiming to achieve a level of clarity and consistency in the responses from the companies a list of questions was prepared by NEL and distributed to representatives of each company prior to individual site visits. These questions are reproduced in the Appendix I of this report.

Five out of the six water companies took part in this part of the project. Due to the sensitivity of the information provided to NEL it was agreed among the members (including DTI) that the specific details of each company's practices should remain anonymous. This report therefore provides a summary of the current practice in the water industry with regards to flowmetering without aiming to specifically highlight the strengths or weaknesses of the individual companies.

A.2 SCOPE OF SURVEY

Water companies utilise flowmeters throughout their businesses from abstraction through to the metering of individual properties and then to flowmetering on the waste water side. It was agreed at the start that the project should concentrate exclusively on the clean (potable) water side and should also exclude revenue metering to avoid detracting from the important issues to be addressed in the study.

A.3 METERING CLASSES

Although the various companies may use slightly differing terminology, the following categorises the various classes of flowmeters that are used throughout their businesses and which have been investigated as part of this survey into current practice.

A.3.1 Abstraction Meters

Abstraction meters measure the abstracted water taken at or very close to the source. Possible sites include: rivers, spring intake, bore-holes, reservoirs. The term

[1] Northumbrian Water were a late addition to the project.

'abstraction' is generally used across the industry although one company refer to their abstraction metering as LARS (Licensed Abstraction Reporting System).

A.3.2 Transmission to Storage Meters

Where water is taken from the abstraction site and stored prior to being pumped or gravity fed to Water Treatment Works (WTW), the water may be metered by Transmission to Storage meters.

A.3.3 Process Meters

Meters that monitor and control the processes at water treatment works are termed Process Meters.

A.3.4 Water into Supply (WIS) Meters

Water leaving WTWs to trunk mains or service reservoirs is measured using Water into Supply Meters. Various terms are used in the industry including: SWORPS (Source Works Output Reporting System), Supply, or DG1 Zones.

A.3.5 Zonal Metering

Zones may either be areas supplied by individual service reservoirs or discrete well defined areas supplied by a particular branch off the trunk main. Various terms are used in the industry to represent a zone including: Production Management Zone (PMZ), District Zones (DZs), Reservoir, and Super District Metering Area (Super DMA).

A.3.6 District Meters

Each zone supplies a number of smaller zones called District Metering Areas (DMA). Each of these DMAs supply a group of properties (industrial and household). The term DMA is used generally in the industry, with the exception of one company who refer to their DMAs as Leakage Control Zones (LCZ).

A.3.7 Transmission/Bulk Flow Meters

Where large volumes of treated water have to be transported long distances there is a special requirement to monitor Transmission Bulk Flows. Only one water company refer to this metering class; the others are able to locate WTW services closer to where the demand is.

A.3.8 Import/Export Meters

Import/Export meters refer to the meters which monitor water transfer from one water company to another. A term used by one water company for their import/export meters is 'Inter-Zonal'.

A.4 FLOW MEASUREMENT: DRIVERS

As described in Section A.3, it has been established that the various water companies have some common ground with regards to the various functions of the business that utilise flowmeters. It is now of interest to discuss the drivers that are in place for these companies in order that that they concentrate effort on flowmetering in the first place, From discussions with the companies it is clear that the predominant driver for them to be able to monitor flows accurately throughout their systems comes from OfWat. Here, each company has to calculate and declare the level of leakage throughout their supply network. The overall aim of OfWat throughout the country is to drive down leakage to an economic level. Flow information from WIS, Zonal and DMA meters are all used in the calculation of the water balance and it is for this reason that many of the companies have concentrated on these meters. Here, efforts have been focussed on not only installing flowmeters so that this balance can be performed, but also employing various methods to be able to demonstrate the accuracy of the data produced from these meters.

Another driver that has stood out is that provided by the Environment Agency (EA) whereby water companies have to be able to accurately monitor the volumes of abstracted water at their various sites. Depending on the specific location in the country and the type of abstraction being performed, there are differing levels of accuracy which the EA legislate. It is for this reason that some water companies may have concentrated effort mainly on ensuring that their abstraction metering is satisfactory and less on being able to demonstrate the accuracy of their water balance.

The various water companies generally agree that both these drivers are important. Where a water company has concentrated more on abstraction meters than meters associated with the water balance, they realise and appreciate the need to address this balance and will generally be making efforts to do this. Likewise it is true for companies where abstraction metering has been of secondary importance.

A.5 SUMMARY OF SURVEY FINDINGS

Following visits to the various water companies to discuss the list of questions (provided in the Appendix), the following represents a condensed summary of the findings from these surveys. This information has been classified into a number of generic headings.

A.5.1 Meter Types

By far the most popular flowmetering technology used in the water industry today, especially when consideration is given to installing a new meter, is the electromagnetic type. For one water company, over the various classes described in Section A.3, they consider that these could account for around 80 to 90% of all their primary metering devices.

Turbine (Helix) meters are another meter type that are used throughout the water industry. These tend to be applied on much smaller diameter pipes and so find application at the DMA level.

Some companies have, on occasion, utilised in-line ultrasonic meters but this certainly is the exception rather than the rule. Ultrasonic clamp-on meters on the other hand have been applied to a greater extent as they provide the advantage of being able to be installed without the need to interfere with the operation of the network. The application of such devices tends to be as a means of flow verification and are therefore only used at a particular location for a short period of time. It is believed however that clamp-on ultrasonic meters have occasionally been used as the permanent and primary means of flow measurement. Clamp-on meters will be discussed in more detail in Section A.5.3.

Insertion probes are commonly used throughout the industry, but these again are predominantly used as a means of verifying the accuracy of the primary device (usually an electromagnetic meter). Having said this, there are again instances where insertion meters have been permanently installed and are being used as a primary measuring device. The use of insertion meters as a form of flow verification is discussed in more detail in Section A.5.3.

Differential Pressure (DP) flow measuring devices (such as orifice plates, Venturis or Dall tubes) are tending to be phased out in the industry with preference being given to the use of electromagnetic meters.

A.5.2 Maintenance/Asset Management

A number of water companies have, or are, in the process of developing their maintenance/asset management systems to include provision for their flowmetering systems. In terms of the flowmeters themselves there is however very little maintenance that they require other than perhaps replacing the batteries on units which have been installed without mains power. Turbine meters are perhaps one exception, whereby these meters may occasionally require the replacement of bearings/blades.

Instead, the maintenance/asset management systems relating to flowmetering is very much geared towards the verification of meter performance. In other words being able to demonstrate that the signal coming out of a flowmeter represents, (within given limits), the actual flow. Discussion of such flow verifications is provided in Section A.5.3.

The following paragraphs describe the experiences of a number of water companies with regards to the application of flow verifications performed as part of their maintenance/asset management systems.

In one company, the planned flowmeter verification/maintenance program is performed by a contractor. In the first year of the program a priority list was prepared of key meters where flow verification/calibration was required. In this first round of assessments a number of meters were found to be reading incorrectly. Furthermore, some of these meters were found to be giving gross errors because they were either not installed correctly or were situated very close to sources of disturbance. Having been through the process of checking, and where necessary. adjusting meter performance once, the company are now in the process of revisiting these meters for a second time. They report that, following the first round of visits, when frequent meter adjustments were necessary, the requirement for further meter adjustments has been found to be the exception.

In another company, a database used to record the details relevant to their flowmetering technology has been in place since 1995. This database can be used for programming all the necessary meter calibrations and includes requirements and costing for civil construction work. It is their intention to examine the flowmeter verifications which have been performed over the years with the aim of determining any trends in flowmeter performance. The aim of such analysis is to allow informed decisions to be made regarding the frequency of such in-situ checks and to determine if predictive or less frequent meter assessments/adjustments could be performed in the future. Since the costs of performing meter verifications throughout the network are very high, the financial benefits of not having to do this so frequently are obvious.

As part of this ongoing verification programme over the past 3 years flowmeters have been examined annually. In the first year of probe assessments around 15% of meters were shown to be out with their required accuracy band. In the second year this figure reduced to around 12% and last year it dropped to around 10%. In-situ checks of new meters were not originally undertaken as a matter of course since the meters came with 12 months warranty. Now, every effort is being made to check the meter calibration at the earliest convenience, thus ensuring that the unit has been correctly commissioned.

Overall, the water companies acknowledge that it would be an excellent idea to compile all the information relating to specific flowmeters in a central flowmetering database. To this end, a number of companies are at various stages in the development of such tools. The sort of information that such a database could include are: location details, type, meter class, manufacturer, size, serial numbers, reference number, installation details, date installed, date last verified, verification frequency, meter adjustments made, meter owner, reference device details, and so on. Such information is crucial if an uncertainty analysis on the accuracy of meter performance is to be carried out.

A.5.3 Verification Methods

From discussions with the water companies there appears to be quite a diversity in the methods used to verify their primary metering devices. Most companies utilise self diagnostic equipment, such as ABB's *Calmaster,* although the extent to which they rely on this method as the principal means of assessing the meters varies quite considerably.

A.5.3.1 Self Diagnostic Equipment

One company which does utilise such self diagnostic equipment as the principle method of verification states that their experience to date is that such technology is a reliable means of assessing the health of their electromagnetic flowmeters. Around 50 verifications using this equipment have been performed with only one registering a problem; an outright failure (of quite an old meter) resulting from water ingress into the coils. However, at a location where a system balance indicated that a meter was likely to be misreading, an in-situ verification check indicated that the meter was operating correctly. It was later found that this meter had been mis-calibrated by the manufacturer. This highlights a problem if such verification techniques are to be considered in isolation from all others techniques. Furthermore, it reinforces the approach adopted by a number of companies who have made provision for secondary verification techniques such as Insertion Probes and Clamp-On Ultrasonics.

A. 5.3.2 Insertion Probe

One company has invested a great deal of effort and expense in the construction of metering chambers where tapping locations for insertion meters have been installed. The procedure adopted for flow verification is to perform 7, 9, 11 or 13 point (depending on pipe size) traverses across the diameter. This information is integrated to calculate the mean flow velocity and the result is compared with the primary flowmetering signal in order to verify it's performance. On specific installations, particularly where there are large diameters and correspondingly high volumetric flowrates, both horizontal and vertical tapping points have been installed. Here, the averaging of the velocity measurements taken across the two traverses aims to take further account of velocity profile effects.

A.5.3.3 Clamp-On Ultrasonic Meters

The company described in Section A.5.3.1 which has invested heavily in providing facilities for probe traverses has reservations about using clamp-on ultrasonic techniques. This is based on its belief that installation effects adversely affect meter readings. Here, it suggests that undisturbed flow should exist for more than 10 diameters upstream of the sensor and acknowledges that a number of its current installations do not provide such ideal conditions. Another concern raised by a number of companies is that they have little confidence in the ultrasonic technique due to past experience where repeat tests have given significantly different results.

In contrast, two other water companies apply this technique as their preferred flow verification technique. Where possible they also support this method of verification with the use of probe measurements. Where there are facilities to be able to perform probe traversing there will generally be just a single tapping point available.

Contrary to the views expressed in Section A.5.3.1 about the poor repeatability of clamp-on meters, one of these companies described that their experience, at various locations, with the repeatability of these devices, has been very good. It was suggested that their policy of calling on the experience of Panametrics staff (who are following best practice) was a possible reason for them finding clamp-on meters more reliable. However, this Water Company aim in the future to be able to perform their own clamp-on measurements and acknowledge that the issue of training is an important consideration. However, it is noted that this company use self diagnostic equipment as their primary means of flowmeter assessment and intend, for the time being at least, not to utilise such clamp-on ultrasonic verifications unless necessary; ultrasonic clamp-on meters are only being used for various ad-hoc flow measurements.

A.5.3.4 Mass Balances

One company, in addition to the use of self diagnostic equipment, utilise an extensive system of mass water balances together with specifically targeted meter verifications where necessary. These system balances are described as being ‘well understood’ allowing judgements to be made about whether flow data appears reasonable or where flowmeter inaccuracy may be causing problems. There are also cases where their network has flowmetering redundancy (i.e. more meters than required to perform a balance) and by careful assessment of one meter against another decisions can be made about their respective performance.

A.5.3.5 Other Techniques: Drop Tests and Thermodynamic Assessment

Other possible techniques which are available to water companies for flow verification include (1) the use of drop tests and (2) thermodynamic assessments on pumped systems. Neither of these techniques are used very often for flow assessment although many of the companies perform drop tests to aid reservoir management and system modelling.

A.5.4 Frequencies of Verifications

The company which utilises probe traversing as its preferred approach for meter verification (in support of their self diagnostic equipment checks) has suggested that a reasonable frequency for performing such verifications is once every 5 years for abstraction and zonal meters and once every 6 years for WIS and DMA meters. These verifications are in addition to the self-integrity checks which are performed once a year and once every 2 years respectively. It is recognised that this company has had its maintenance and asset management system in place since around 1995 and therefore has had the experience to make such judgements.

In contrast, a number of other companies who are recently up and running with their verification systems, perform probe traversing and clamp-on techniques on an annual basis.

Another company who carry out probe traverses as part of its verification procedures, associated with network or trunk main modelling, perform these around once every three years or so.

A.5.6 Data Collection: Loggers and Telemetry Systems

Two main methods are used by the water companies for the collection and storage of flowmeter data: direct logging using dedicated loggers located at the metering site, or through telemetry. Generally speaking, the water industry tends to use telemetry systems with the abstraction and WIS meters, and loggers primarily on zonal and DMA meters.

A.5.6.1 Loggers

With regard to the collection and storage of flowmeter data at one of the companies, a system of data loggers is in place at their zonal and district metering sites. The majority of its sites are monitored in this way with further effort being focussed on completing the coverage of district metering. Pulsed data is logged continuously at these sites and downloaded over telephone lines. An audit procedure (end to end check) is regularly performed to compare this logged data with the on-site meter readings. The company indicated it is very content with this system and stated that these data sets match up very well. However, they did express a concern with buried battery powered electromagnetic meters. These meters are described as having been regularly found to fail and it is now their common practice to install the meters in chambers.

These Zonal and District meters are demand dependent and flow may well vary considerably depending on the time of day. Since it is not possible to control the flowrate without interruption, it is the preferred procedure to perform this task of data collection over a 24-hour time interval. A best-fit line is generated between the pulsed output of the meter versus flowrate using spreadsheet functions. The equation of this line is then used to determine the offset error (to specify zero flow) and the range error (to factor the output across the range). Following such an in-situ meter verification the flowmeter may be adjusted and a repeat calibration performed.

Another company which utilises data loggers in a similar way has good experience using mainly the pulsed frequency output of the meters. Tests comparing the pulsed output with the comparable analogue signal were found to give identical results. The reason for this is that the meter electronics use the pulsed signal to generate the analogue signal. It was stated that before the improvements in flowmetering technology, electromagnetic meters did tend to drift somewhat.

This company also use dedicated data loggers on their WIS metering sites so that there is a traceable match between the archived data in their database and the actual source data at each meter. They say that they are currently using an old telemetry system but are trying hard to get away from using it as a means of capturing flow data. The reason for this is said to be because the telemetry system only takes snap-shots of data and the system was never designed, or intended to be used, for such a data gathering exercise; instead it was designed very much as an operational tool. The intention of the company is to use dedicated data loggers which are linked back to a central office for archiving using telephone line technology. Their DMA meters are also logged continually.

A logging frequency of 15 minutes is used, although the loggers could be set up to log at a very much higher frequency if required. The data archiving system has a sophisticated ‘out of limits’ algorithm which is described as being ‘self-training’. This has the facility to enter a range over which the normal operating conditions of a meter will lie and for an e-mail to be sent to the meter owner when the meter signal is out this range. This system is not utilised at present and is viewed as a possible future development.

A.5.6.2 Telemetry Systems

The common feature across the various telemetry systems used in the water industry is that it is the analogue flow velocity output that is captured on telemetry. This is despite the fact that modern electromagnetic flowmeters generate volumetric flow information through their pulsed output channels. One problem with this analogue outputs is that the data from telemetry still has to be integrated in order to generate the necessary volumetric flow information. The flowmeter itself performs such an integration by performing a rolling average, with perhaps 20 mean flow measurements being made per second. The telemetry system on the other hand is polling the mean flow rate say just once every 15 seconds.

In recognition of the potential problems with data obtained through telemetry the following issues are reproduced from the experience of one of the contributing water companies to the project.

Problems On Site

It is recognised by this Water Company that the accuracy of the flowmeter’s primary device could have the greatest impact on the quality of data on site. The company have performed site surveys at 23 of their largest WIS sites in order to assess these meters.

Secondary device checks are generally performed periodically but there are issues relating to older meters where secondary device simulators are not available. They also report that the checking of site readings with telemetry is seen as a nuisance, partly because this task cannot be performed locally. Telemetry checks at older installations, where telemetry checks are made with separate site integrators, have also indicated problems. As these older meters are replaced with meters which provide integrated flow data, this problem is described as slowly disappearing. The EA have apparently requested manual site readings from separate integrators at abstraction sites and this has been highlighted as a potential problem because of the unavailability of secondary device simulators.

Since there is a requirement for new meters to be included on the telemetry system it is considered that any problems with meter installation and set up will be identified at an early stage through the commission process. It has been highlighted, however, that instances have occurred where new meters have been installed and operating for several months before it is realised that it has not yet been put on telemetry. They consider that a way of improving this situation is to have data verifiers who also have instrumentation responsibilities.

Telemetry Problems

The main problem with telemetry, as described by this company, is the inadequate checking of the telemetry integration sequence. At the time of commissioning of a new meter, or following changes to a meter calibration, there is a need for either a new or modified flow integration sequence (program). Following such changes, a comparison of telemetry and site integrations is required, and this should be performed over a time period of at least 24 hours. They also highlight that resource problems is the reason for the lack of integration checks, where such a procedure requires site readings to be performed twice over the time interval. There are also issues relating to telemetry personnel not always being informed of changes to flow meters on site. This problem, where there is ignorance of the implications of the impact of such changes on telemetry, is described as being most severe when data verifiers do not have responsibility for the instrumentation and instead serve a role of technical clerks.

There are also issues relating to outstation resets or sequence reloads. Here total daily flows, prior to the change, are lost and the database storing the telemetry data would be erroneous. Moves are being made at this water company to have an automatic procedure in their telemetry system which flags such data as being invalid.

Data Verification Issues

In 1999 this company launched a new web browser application for use with their telemetry system. This system replaced the old Vax-based application. One of the data quality issues relating to the old system was the habit of some verifiers needlessly changing daily flow values collected by telemetry. Here, these daily figures were replaced with averaged values based on the weekly or fortnightly flow data collected on site. This led to 7 or 14 day periods in the database being populated with identical daily flow values.

In the new system such manual editing of the telemetry database is now regarded to be the exception rather than the rule. Automatic verification procedures are in place which check daily telemetry data against set limits derived from statistically ‘good’ data. These procedures include the ability to set limits for seasonal, weekly, daily and rate of change variations where applicable. Since the introduction of the new system there has been a sharp decrease in the amount of altered data with an additional 10% now passing verification. The total amount of data still failing verification is now just 5%.

APPENDIX A1 –

'WM04 - General Questions for Water Companies'

(1) Do you have an overall calibration programme implemented in your water company?

(2) Do you have a database of all your meters, what is included on it, eg calibration status – do you use this to examine trends? Do you notice any consistency in these trends? Do you have a priority with regards to which class of meters required to be calibrated and to what level of accuracy?

(3) Do you record in this database the meter calibration method? eg availability of insertion points (horizontal and vertical)? Which meter classes have more than one tapping location? What is the breakdown of meters with calibration pits and those without? Are the buried flowmeters accessible for calibration in the future or are they buried in concrete?

(4) Are these calibration pits suitable for the use of clamp-on meters? Do you use such in-situ calibration techniques? Do you have calibration pits positioned in roads or do you aim to utilise the self diagnostics of the meters together with comparison with other meter installations elsewhere in the system?

(5) Do you utilise flowmeter self diagnostics eg Calmaster? What are your experiences of these systems? When would you use such systems – e.g. when nothing else is available or in preference to full calibrations?

(6) In probe calibrations, how many points across the traverse do you do or is it simply a D/8 (7/8D) point velocities you measure? What integration techniques do you do with the traverse data in order to calculate the mean flow? Have you assessed the uncertainties in these calculations? What is the largest diameter of pipe you would use a traversing technique on?

(7) If you use insertion probes with customised computer software do you simply input the pipe diameter and number of profiling points? How do you determine pipe diameter? Do you remove the pipe in order to take a number of readings (so you can take an average e.g.6 readings) or do you utilise commercial gauges that can be implemented from the same tapping set-up as the insertion meter?

(8) Can you be assured that the flow rate during the traverse(s) remain constant? Do you normalise the probe measurements with a reference measurement such as a local full-bore readout or pump/fan speed?

(9) Are probe traverses performed at locations where the flow may not be reasonably well developed or may have swirl or asymmetry?

(10) Do you have traceable calibrations of probes? How often? Would you generally determine a single calibration factor across the range of flows or look to determine a best fit between error versus flow rate and use this to correct the insertion meter readings?

(11) Do you do both a probe and self diagnostic checks?

(12) Do you utilise thermodynamic calibrations on pumped systems whereby total energy balances (incorporating pressure and temperature measurements) can be used to determine flow discharge for comparison with the test meter? Have you assessed the uncertainties in these calculations? Have you tried evaluating this technique on meters where an insertion probe could also be utilised?

(13) Following a meter calibration do you adjust the meter so it is more accurate or do you correct the data from the meter on the basis of the calibration result? Who has the authority to perform meter adjustments? Are these always documented?

(14) Do you replace meters instead of calibrating them – e.g. on small diameter mains where there may be no possibility to adjust the meter if found to be in accurate?

(15) Do you have meters where calibration is designated as 'not required' – what/where/why….?

(16) Do you have any meters which are unable to be calibrated at all - ie not by: (1) probe, (2) self integrity check, (3) combination of probe and self integrity check, (4) thermodynamic, (5) replacement or (6) not required.

(17) Could you provide a breakdown of the different types of meters you have in each of the meter classes together with the corresponding methods of calibration? Which manufacturers make these meters?

(18) Are there other calibration techniques which you do not employ – eg clamp-on ultrasonics or drop tests? If you do drop tests how do you accurately measure changes in water depth in the reservoir?

(19) Flow rates over which calibrations are performed - do you have different techniques of comparing meter and test units for different meter classes, e.g. abstraction and supply metering may be pumped systems. Here, are comparisons made between zero flow and full operating flow? If a station has multiple pumps do you compare them at other flow rates? Do you compare meter and test unit figures after a meter adjustment?

(20) Reservoir and district meters are different because they are demand dependent. Here a calibration across a range of different flowrates cannot be performed without interruption – do you accept such interruptions or do you log the data from these meters eg over a 24 hour period and analyse the data accordingly?

(21) Regarding adjustments to meters following a calibration – for Abstraction and Supply meters do you perform a zero flow test and adjust the 4 mA accordingly? Similarly, when operating at a normal operating range are any of the remaining errors corrected for by adjusting the velocity range setting of the meter?

(22) In reservoir and district metering how are the off-set and range errors determined – eg is a best fit straight line of meter versus probe data used to determine these characteristics?

(23) What systems are in place to assess the accuracy of secondary instrumentation such as chart recorders, counters and telemetry systems?

(24) What is your position with regards to the setting up and implementation of a calibration programme? What classes of meters are currently being considered and can you provide a history of the development of your programme?

(25) Can you provide a breakdown of the number of meters in each class which are able/unable to be calibrated and the methods used for these calibrations?

(26) What accuracy targets have you set for each of your meter classes? Is there any strategy regarding how many tappings each class of meter has? Is this dependent on the size of the pipe – eg do pipe sizes above a certain amount typically have two tappings? How frequently do you calibrate your meters? Do you distinguish between full calibrations (calibration and adjustment) and footprinting (calibration without adjustment).

(27) Do you have any plans for meter replacement of older, potentially less accurate, meters (eg differential pressure meters such as orifice and Venturi meters)? Do you intend replacement with electromagnetic meters? Do you aim to incorporate the self diagnostic capabilities that are available from a number of flowmeter manufacturers when meters are replaced?

(28) What lifetime would you expect to achieve from your meters before replacement? Would this form part of a replacement strategy or would they be replaced when they breakdown? Is this the same across all meter classes?

(29) Do you have guidelines relating to straight upstream and downstream pipe lengths of meter and tapping locations? What number of straight length diameters would you aim to achieve and what would be typical in practice for each of the meter classes?

(30) What is the state of play regarding your meter referencing system – could a meter have more than one reference number? Can each meter be located easily or is there potential for meters referred to on site plans not to match up? Are there implications for management of data retrieval/ archiving systems? What Q&A procedures are in place to prevent databases being corrupted by erroneous modifications?

APPENDIX B

GENERAL GUIDELINES FOR ESTIMATING THE UNCERTAINTY OF FLOW MEASUREMENTS IN THE WATER INDUSTRY

APPENDIX B –

GENERAL GUIDELINES FOR ESTIMATING THE UNCERTAINTY OF FLOW MEASUREMENTS IN THE WATER INDUSTRY

B.0 GLOSSARY OF TERMS

Absolute Uncertainty – The absolute uncertainty is the number which, when combined with a reported value, gives the range of values within which the true value is considered (to a given level of confidence) to lie. Absolute uncertainties always have the same units as the reported values.

Correlated Uncertainty – Input components to a system uncertainty can be correlated or non-correlated. A correlation means that the input components have both been influenced in a similar way by procedures. For example, consider flowmeters installed at two separate abstraction sites which are used to monitor the total water going into a Water Treatment Works. Although the sites may differ substantially in terms of location, pipe size, flowrates and so on, the in-situ verification checks (and potential meter adjustments) could well have been carried out by the same personnel using the same equipment. In such a case it would be expected that the data from the two meters would be correlated to a certain degree.

Coverage Factor – In general, the value of the coverage factor, (often expressed as '*k*'), is chosen on the basis of the desired level of confidence to be associated with the range in which the true value of the measurement is thought to lie. For example, as described in 'Standard Uncertainty', a coverage factor of 2 when applied to a normal distribution results in a 95% level of confidence that the measured value will lie within the range of the mean ± two standard deviations.

Expanded Uncertainty – Standard uncertainties are defined at the one standard deviation level. When a coverage factor of two is applied, for example in a normal distribution k = 2 giving a 95% confidence interval, the expanded uncertainty is the increased range within which a new measurement is expected to lie. i.e. the expanded uncertainty with a coverage factor of 2 represents the two standard deviation interval. Higher coverage factors result in an increased range and so the confidence interval also increases.

Monte Carlo Analysis (Simulation) – This is a computer-based method of analysis developed in the 1940's that uses statistical sampling techniques to obtain a probabilistic approximation to the solution of a mathematical equation or model.

Random Error – A random error is the result of a measurement minus the mean that would result from an infinite number of measurements of the same quantity carried out under the same conditions.

Relative Uncertainty – The relative uncertainty is the ratio of the absolute uncertainty to the reported value and is commonly expressed as a percentage.

Sensitivity Coefficients – Sensitivity coefficients (factors) relate the uncertainty on a measurement to the uncertainty in the final result. Consider, for example, the uncertainty in an internal diameter measurement of a pipe, and the extent to which this affects the uncertainty in the calculated cross sectional area (assuming perfectly smooth and round). If the diameter measurement uncertainty is ± 2%, then this results in an uncertainty in area of 4%. The sensitivity of area to diameter is therefore two. NB Since flowrate is directly proportional to the product of mean flow velocity and cross sectional area, a relative uncertainty in diameter, for the same mean flow velocity, introduces twice the uncertainty in flowrate.

Standard Uncertainty – Each component of uncertainty, however evaluated, is represented by an estimated standard deviation, termed standard uncertainty. For a population with a normal distribution, around 66% of the population would be within the ± one standard deviation interval. Similarly, for a coverage factor of 2, around 95% of the population would be within the ± two standard deviations interval.

System Uncertainty – An uncertainty analysis involves identifying all the components which contribute to the uncertainty of the overall system. The system uncertainty is simply the result of the calculation when all these component uncertainties have been taken into account.

Systematic Error – The systematic error is the difference between the mean from an infinite number of measurements of the same quantity and the true value.

Type A Evaluation – This is the method of evaluation of uncertainty by the statistical analysis of a series of observations. This analysis will statistically estimate the standard deviation (standard uncertainty) of the sample.

Type B Evaluation – This is the method of evaluation of uncertainty other than by means of the statistical analysis of a series of observations. Type B evaluations require knowledge about the probability distribution associated with the uncertainty component. This component can be considered to be an approximation to the corresponding standard deviation (standard uncertainty) as calculated with a Type A evaluation.

Un-correlated Uncertainty – Input components to a system uncertainty are un-correlated when both inputs are independent from each other. For example, the uncertainty in the measurement of flow using a clamp on is influenced (amongst other things) by the accuracy of the cross sectional area measurement of the pipe and the extent to which the installation disturbs a fully developed velocity profile. These two inputs to the uncertainty analysis are un-correlated.

B.1 INTRODUCTION

The Water Industry is reliant on information from flow measurements for its commercial and regulatory business. Information derived from flow measurements is used in many different ways and for many different reasons throughout its business.

Whenever a measurement is made the reported flow reading is only an estimate of the flow at the point of measurement and at the time the measurement was made. The flow reading then undergoes many forms of processing before it is eventually reported as a result.

Therefore, any reported results derived from measurements made by flowmeters are only approximations and are not absolute measurements in the same way that other statistical estimates (such as per capita consumption and population estimates) are only approximations. When population estimates are made only a sample of the population is represented at a particular point in time this is also true in the case of a flowrate measurement.

Therefore, the final reported result is only an estimate of the flow and by definition any estimate has associated with it a certain degree of doubt. Both managers and regulators need to know the accuracy of reported results since important operational and management decisions, and target setting, possibly with huge financial implications, are based on these results.

A methodology for assessing the accuracy of measurements that has received international acceptance is the evaluation of measurement uncertainty. This methodology gives guidance on how to assess the reliability of a measurement or ‘evaluate the uncertainty of measurement’.

This general guidance document for estimating the uncertainty of flow measurement in the Water Industry is based on this internationally accepted uncertainty methodology. The document will show that use of this uncertainty methodology can give better and more cost effective solutions to demonstrating confidence in results than those currently in place.

General guidelines are given in Appendix B1 on how to implement the uncertainty methodology. Following this, in Appendix C, the application of the uncertainty methodology discussed here is applied, by way of example, to a specific Water Industry scenario.

B.2 THE METHODOLOGY

B.2.1 Definition of Requirements and the Measurement Process

Measurements of flow are made using a flowmeter so it is reasonable to assume that what is required is the uncertainty of measurements from that flowmeter but the flowmeter may provide a number of different outputs (for example instantaneous flowrate or totalised volume passed). Often the results of measurements from several flowmeters are combined to give total volume (e.g. from a particular treatment works). More generally, flows are combined with other parameters such as per capita consumption or population estimates to give reported results such as leakage or water balance.

Initially, the whole measurement system needs to be examined by top level managers to determine what final results are important to the business. These need to be prioritised and managers then need to set target uncertainties for these results. It may be difficult to set targets, either because targets may not be achievable with the existing technology or meeting the targets may be too expensive, so an initial estimate of the uncertainty using the existing flowmeters and processing procedures is required.

The important factor is that top level managers define what results are required and prioritise them. Once these results have been defined the derivation or calculation of these results needs to be very clearly stated.

Once the calculation procedure has been defined then attention can be focused on the flow measurements and the individual flowmeters. These calculation procedures need to be included within the company's quality procedures, since a change in the procedure could effect a change in the uncertainty of the result produced by following that procedure.

B.2.2 The Level of Uncertainty Analysis

There may be different reasons for performing the uncertainty analysis. For example, one reason is to calculate the overall uncertainty of the whole measurement and reporting process, another reason is the identification of major sources of uncertainty within that system. If the overall system uncertainty is too high then major sources of uncertainty need to be identified and action taken to reduce the overall uncertainty.

The overall system uncertainty will have been determined based on many assumptions and possibly expert judgements and engineering assessments. Depending on their significance these assumptions will require to be verified and a more detailed assessment of uncertainty made for components of uncertainty with significant contributions to the overall system uncertainty. It is also vital to ensure that no major sources of uncertainty are missed or wrong assumptions made which have a significant effect on the overall uncertainty.

Therefore, it is clear that there are different levels at which uncertainty analysis can be performed, from a top-level analysis such as identifying the overall uncertainty of a complete measurement and reporting process through to assessing the uncertainty of an individual flow measurement or a calibration procedure. An example of a very detailed level of analysis may be identifying major contributions to the uncertainty in a particular procedure such as assessing the difference in uncertainty in performing a five or nine point insertion meter traverse for calibration purposes. The detailed analysis is required to assess the uncertainty in the procedure but also to ensure that major sources of uncertainty have not been ignored.

B.2.3 Correlated and Un-correlated Sources of Uncertainty

If the same procedure is being used to generate data from more than one input component then there is a strong possibility that the information in these components will be correlated. i.e. the components are all affected to a degree by uncertainties associated directly with the procedures. For example, the same test equipment may be used by the same member of staff at different sites. The degree of correlation will depend on the procedure. Another example is flowmeters of the same type, and from the same manufacturing batch; these are highly likely to exhibit similar characteristics whereby they may all tend to drift in the same direction over time or all tend to over-read or all tend to under-read. The degree of correlation needs to be assessed.

B.2.4 Systematic and Random Effects

These effects may be important depending on the application and these concepts need to be considered in relation to the final result. The input component uncertainty cannot be systematic or random but it can effect the result in a systematic or random manner.

Take the example of the calibration of a flowmeter where the average of a number of readings from that flowmeter is used to obtain the flowrate. Generally, systematic effects will affect the overall result in the same way no matter how many readings are taken whereas random effects can be reduced by taking more readings. Therefore, the concepts of systematic and random effects are required to identify the correct course of action in order to reduce uncertainty. When the overall uncertainty is dominated by systematic effects this points to another course of action such as using instrumentation with a lower uncertainty. When systematic effects dominate, no matter how many readings are taken, the uncertainty will not be significantly reduced. An appreciation of systematic and random effects is important because the acquisition of large data sets, which may be expensive and time consuming, may not significantly improve the overall uncertainty. In other cases expensive high specification flowmeters may be purchased when all that was required was a larger data set.

B.2.5 Absolute and Relative Readings

The uncertainty analysis is different depending on the required information. If an absolute figure is required, for example the total distribution input over a one-year period, then correlated and systematic effects are important. If, however, a relative difference is required or the flowmeter is only used to detect a change in the process, then correlated and systematic effects very often cancel each other out and therefore do not require to be assessed.

For example, take the case of two similar flowmeters measuring flow in a pipe and one is placed some distance upstream of the other so that the difference in flowrates from these two meters could be used to indicate leakage between the two meters. If both flowmeters are very accurate then the difference would be leakage. However, if both meters have similar characteristics and, for example, they both over-estimate the flowrate by the same amount, then the difference between the two flow readings would still give leakage to the same level of uncertainty even although the two meters were not absolutely accurate. Another example is where the two meters are both calibrated wrongly. This can be explained generally as follows:

$$(\text{Meter A} + \text{Error}) - (\text{Meter B} + \text{Error}) = \text{Difference}$$

From the equation above it can be easily seen that, provided the error is the same in both meters, the errors cancel each other out.

An example of detecting a change is given generally as follows:

$$(\text{Meter A} + \text{Error})_{@\ \text{time } t=0} - (\text{Meter A} + \text{Error})_{@\ \text{some time later}} = \text{Change}$$

As has been demonstrated above, it is important to know whether an absolute value is required or not, since effort in obtaining an absolutely accurate measurement can be reduced. However, caution should be exercised in making assumptions and random or un-correlated effects may still be significant.

B.2.6 Two Stage Approach

In order to make an estimation of uncertainty at any level, the task is split into two distinct stages:

- the data gathering stage
- the calculation or evaluation stage

As stated above all calculations and procedures need to be clearly defined. All sources of uncertainty will need to be identified and an estimate made of the uncertainty in each source. This is the data-gathering stage. The calculation or evaluation stage is then simply the calculation of the overall uncertainty from the individual sources of uncertainty.

The variables or components that are used as inputs to the procedure or calculation are termed 'input components' and the final result or measurement is termed the 'output component'. A simple example is the calculation of volumetric flowrate from the velocity and the cross-sectional area of the pipe. In this example, both the velocity and the cross-sectional area are the input components and the volumetric flowrate is the output component or the result.

In the estimation of the uncertainty of a complete system or process involving many flowmeters, the data-gathering stage will require an estimate of the uncertainty in the measurements made by individual flowmeters.

B.3 SOURCES OF UNCERTAINTY

This section describes how to perform the data-gathering stage for an individual flowmeter. All sources of uncertainty need to be identified and consideration should be given to evaluating the uncertainty in:

- the flowrate itself (flowrate is dynamic and varies over the measuring period)
- uncertainty in the actual flowrate measurement using a flowmeter
- any additional installation effects
- any effect due to deviation from a meter manufacturer's specification
- any effect due to deviation from procedure or applicable engineering standard
- calibration uncertainty
- data sampling and averaging method
- the data transmission
- data processing

It is important within the above sources of uncertainty listed above that consideration is given to all input components to the calculation of an overall result, whether they are measured or not. For example, leakage figures are not directly measured, but are used in the water balance. It is still necessary, however, to evaluate an uncertainty associated with the leakage figure being assumed.

B.4 EVALUATING UNCERTAINTY

B.4.1 The GUM

The authoritative international guide relating to measurement uncertainty is the Guide to the Expression of Uncertainty in Measurement (GUM) published by the International Standards Organisation (ISO)(1). The draft international Standard ISO/CD 5168(2) follows the GUM methodology and gives specific guidelines for the evaluation of uncertainty in flow measurement.

B.4.2 Type A and B Uncertainty

In the GUM and in the ISO/CD 5168 methodologies, input component uncertainties can be estimated in one of two ways. Either they are derived using statistical methods (termed Type A evaluation) or by other means (termed Type B evaluation). Appendix B1.1 and B1.2 gives the methods for deriving uncertainty estimates for Type A and Type B components, respectively.

B.4.3 Sensitivity Coefficients

Before considering methods of combining uncertainties, it is essential to appreciate that it is insufficient to consider only the magnitudes of component uncertainties in input quantities, it is also necessary to consider the effect each input quantity has on the final result. It is therefore convenient to introduce the concept of the sensitivity of an output quantity or result to a change in the value of an input quantity. The sensitivity coefficient is used to quantify this effect. There are two ways to determine the sensitivity coefficient either numerically or analytically. These methods are described in Appendix B1.3.1 and B1.3.2, respectively.

B.4.4 Evaluating the Overall Uncertainties

Finally, the method of calculating the overall uncertainty from both the component input uncertainties and sensitivity coefficients is given in Appendix B1.4.

B.4.5 Standard and Expanded Uncertainty

The GUM methodology reduces all the component uncertainties to what it terms standard uncertainties. This method is specified so that uncertainties with varying levels of coverage can be reduced to one common denominator. Standard uncertainties are defined at the one standard deviation level. In flow measurement the coverage factor is normally specified to give a confidence level of around 95%. This means that the result, y, if recalculated using the same procedures and the same measuring instruments is expected to lie within the range y+U to y-U (where U=expanded uncertainty) 19 out of 20 times.

B.4.6 Absolute and Relative Uncertainties

In general, the choice to work in absolute uncertainty (units) or relative uncertainty (%), is of little consequence. However, care is needed to ensure that all uncertainties are expressed in the same terms. Measurements with arbitrary zero points can give rise to problems if uncertainties are expressed in relative terms. Relative uncertainties cannot be used in these circumstances and absolute uncertainties must be used. Therefore, it is recommended to use absolute uncertainties wherever possible in order to reduce mistakes.

B.5 OTHER CONSIDERATIONS

Whilst no correction can be made to remove random components of uncertainty, their associated uncertainty becomes progressively less as the number of measurements increases. In taking a series of measurements it must be recognised that the purpose is to define the random fluctuations in the process, the timescale for the data collection should therefore reflect the anticipated timescale for the fluctuations. Collecting readings at millisecond intervals for a process that fluctuates over several minutes will not characterise those fluctuations adequately. However, in a time varying flowrate situation such as a demand-dependent supply from a reservoir, taking a large number of repeat flow measurement readings may not converge towards the correct answer. This is because the flowrate may be reducing (or increasing) throughout the entire period the measurements are being made.

In many measurement situations it is not practical to make a large number of measurements: in this case this component of uncertainty may have to be assigned on the basis of an earlier Type A evaluation, based on a larger number of readings carried out under similar conditions. Caution should be exercised in making these estimates as there will always be some uncertainty associated with the assumption that the earlier measurements were taken under truly similar conditions.

Due to its technology the flowmeter may only sample part of the flow. For example, it may take a local or point velocity reading (e.g. an insertion probe) or it may average the flow across a diameter of the pipe cross section (e.g. a single path ultrasonic meter). Even full bore meters such as electromagnetic meters will still average the flow across the whole pipe cross section and over a specified time interval; the averaging method will be related to its technology and its internal post-processing procedures.

B.6 STEP-BY-STEP PROCEDURE

1. Identify the end results required and the expected uncertainty
2. Define and document the measurement process, system or procedure for obtaining the required results
3. Ensure any specified engineering standards, procedures or manufacturers recommendations are followed
4. Ensure all procedures are included in the Company quality system and full audit procedures are in place
5. Identify and document any calculations
6. List the input components or parameters
7. Estimate the uncertainties of the input components
8. List any additional sources of uncertainty
9. Estimate the uncertainties of the additional sources
10. Calculate or estimate the sensitivity coefficients
11. Identify any correlated uncertainty sources
12. Calculate the overall uncertainty

B.7 APPLICATION OF UNCERTAINTY ANALYSIS - EXAMPLE

Appendix C, which follows after Appendix B1, applies the uncertainty methodology discussed in this section to a specific Water Industry scenario.

B.8 REFERENCES

1 Guide to the Expression of Uncertainty in Measurement (GUM) – Published by the International Standards Organisation.

2 ISO/CD 5168 – draft international Standard.

APPENDIX B1 –

UNCERTAINTY CALCULATION PROCEDURE

B1.1 Type A Evaluation of Uncertainties

Further explanation of the formulae and terminology used given below can be found in ISO/CD 5168[2]. The standard uncertainty, $u(x_i)$ of a measured value x_i is calculated from a sample of 'n' measurements $x_{i,k}$ as follows:

1 Calculate the mean value of the sample of measurements

$$\overline{x}_i = \frac{1}{n}\sum_{k=1}^{n} x_{i,k} \qquad [B1.1]$$

2 Calculate the standard deviation of the sample

$$s(x_i) = \sqrt{\frac{1}{(n-1)}\sum_{k=1}^{n}\left(x_{i,k} - \overline{x}_i\right)^2} = \sqrt{\frac{n\sum_{k=1}^{n}\left(x_{i,k}\right)^2 - \left(\sum_{k=1}^{n} x_{i,k}\right)^2}{n(n-1)}} \qquad [B1.2]$$

The standard uncertainty of a single sample is then given by

$$u(x_i) = s(x_i) \qquad [B1.3]$$

3 Calculate the standard deviation of the mean value

$$s(\overline{x}_i) = \frac{s(x_i)}{\sqrt{n}} \qquad [B1.4]$$

The standard uncertainty of the mean value is then given by

$$u(\overline{x}_i) = s(\overline{x}_i) \qquad [B1.5]$$

B1.2 Type B Evaluation of Uncertainties

B1.2.1 Definition

Type B evaluations of uncertainty are those carried out by means other than the statistical analysis of a series of observations and are usually based on a pool of comparatively reliable information (see Section 4.3 of the GUM[1]).

B1.2.2 Calculation Procedure

Type B evaluations of uncertainty require knowledge of the probability distribution associated with the uncertainty. The most common probability distributions are give below.

B1.2.3 Rectangular Probability Distribution

Typical examples of rectangular probability distributions include

- Maximum instrument drift between calibrations
- Error due to limited resolution of an instrument's display
- Manufacturers' tolerance limits

The standard uncertainty of a measured value x_i is calculated from

$$u(x_i) = \frac{a_i}{\sqrt{3}} \qquad [B1.6]$$

where the range of measured values lies between $x_i - a_i$ and $x_i + a_i$

B1.2.4 Normal Probability Distribution

Typical examples include

- Calibration certificates quoting a confidence level or coverage factor with the expanded uncertainty: here the standard uncertainty is calculated from

$$u(x_i) = \frac{\text{expanded uncertainty}}{k} \qquad [B1.7]$$

where k is the quoted coverage factor.

Where a coverage factor has been applied to a quoted expanded uncertainty, care should be exercised to ensure that the appropriate value of k is used to recover the underlying standard uncertainty. However, if the coverage factor is not given or the 95% confidence level is quoted then k should be assumed to be 2.

B1.2.5 Triangular Probability Distribution

Some uncertainties are given simply as maximum bounds within which all values of the quantity are assumed to lie. There is often reason to believe that values close to the bounds are less likely than those near the centre of the bounds, in which case the assumption of rectangular distribution may be too pessimistic: in this case the triangular distribution may be assumed as a prudent compromise between the assumptions of a normal and a rectangular distribution.

$$u(x_i) = \frac{a_i}{\sqrt{6}} \qquad [B1.8]$$

For example, taking the difference between two readings of total volume recorded by a water meter is subject to a reading error which could be assumed to have a triangular probability distribution.

B1.2.6 Bimodal Probability Distribution

When the error is always at the extreme value then a bimodal probability distribution is applicable and the standard uncertainty is given by

$$u(x_i) = a_i \qquad \text{[B1.9]}$$

Examples of this type of distribution are rare in flow measurement.

B1.2.7 Asymmetric Probability Distributions

The above cases are for symmetrical distributions. However, it is sometimes the case that the upper and lower bounds for an input quantity X_i are not symmetrical with respect to the best estimate x_i. In the absence of information on the distribution, the GUM recommends the assumption of a rectangular distribution with a full range equal to the range from the upper to the lower bound. The standard uncertainty is then given by

$$u(x_i) = \frac{b_1 + b_2}{\sqrt{12}} \qquad \text{[B.10]}$$

where $x_i - b_i < X_i < x_i + b_i$

A more conservative approach would be to take a rectangular distribution based on the larger of two asymmetric bounds.

$$u(x_i) = \text{greater of } \frac{b_1}{\sqrt{3}} \text{ or } \frac{b_2}{\sqrt{3}} \qquad \text{[B.11]}$$

If the asymmetric element of uncertainty represents a very significant proportion of the overall uncertainty it may be more appropriate to consider an alternative approach to the analysis such as a Monte Carlo analysis.

B1.3 Sensitivity Coefficients

The sensitivity coefficient of each input quantity is obtained in one of two ways:

- Analytically
- Numerically

B1.3.1 Analytical Solution

When the functional relationship is specified, the sensitivity coefficient is defined as the rate of change of the output quantity y with respect to the input quantity x_i, and the value is obtained by partial differentiation

$$c_i = \frac{\partial y}{\partial x_i} \qquad \text{[B.12]}$$

However, when non-dimensional uncertainties, for example relative uncertainties (%), are used, non-dimensional sensitivity coefficients must also be used, where

$$c_i^* = \frac{\partial y}{\partial x_i}.\frac{x_i}{y} \quad [B.13]$$

In certain special cases where, for example, a calibration experiment has been made, the functional relationship between the input and output is simple and the value of c_i or c^*_i may be unity.

For example, if all the components have a simple addition or subtraction relationship such that:

$$f(y) = x_1 \pm x_2 \pm x_3 \pm \ldots\ldots \pm x_l \quad [B.14]$$

Then the standard uncertainty is simply given as follows:

$$u(y) = (u_1^2 + u_2^2 + u_3^2 + \ldots\ldots + u_l^2)^{½} \quad [B.15]$$

If all the components multiply or divide by each other such that:

$$f(y) = x_1\, x_2\, x_3 \ldots /\ x_4\, x_5\, x_6 \ldots \quad [B.16]$$

Then the standard uncertainty is simply given in relative terms as follows:

$$u(y)^* = [(u_1^*)^2 + (u_2^*)^2 + (u_3^*)^2 + \ldots\ldots + (u_l^*)^2]^{½} \quad [B.17]$$

where $u_l^* = (u_l/x_l) \times 100$ and is the percentage relative uncertainty.

Any other more complex functional relationship will include sensitivity coefficients that are not unity and will require to be carefully evaluated. An example of such is given in Appendix C.

B1.3.2 Numerical Solution

Where no mathematical relationship is available, or the functional relationship is complex, it may be easier to obtain the sensitivity coefficients numerically, by calculating the effect of a small change in the input variable x_i on the output value y.

First calculate y using x_i, and then recalculate using $(x_i + \Delta x_i)$, where Δx_i is a small increment in x_i. The result of the recalculation can be expressed as $y + \Delta y$, where Δy is the increment in y caused by Δx_i.

The sensitivity coefficients are then calculated from

$$c_i \approx \frac{\Delta y}{\Delta x_i} \quad [B.18]$$

In non-dimensional, or relative, form

$$c_i^* \approx \frac{\Delta y}{\Delta x_i}.\frac{x_i}{y} \quad [B.19]$$

Table B1.1 shows how a typical spreadsheet could be set up to calculate a specific sensitivity coefficient for any function where $y = f(x_1, x_2, \ldots, x_N)$

Table B1.1 — Spreadsheet Set-up for Calculating Sensitivity Coefficients

Sensitivity Coefficient	Increment	x_1	x_2	...	x_i	x_N	y	c	c^*
	-	x_1	x_2	...	x_i	x_N	$y = f(x_1, x_2, ..., x_N) = y_{nom}$		
c_1	$\Delta_1 \approx 10^{-6} \times x_1$	$x_1 + \Delta_1$	x_2	...	x_i	x_N	$y = f(x_1 + \Delta_1, x_2, ..., x_N)$	$(y_1 - y_{nom})/\Delta_1$	$c \times x_1/y_{nom}$

The analytical solution calculates the gradient of y with respect to x_i at the nominal value x_i, whereas the numerical solution obtains the average gradient over the interval x_i to $(x_i + \Delta x_i)$. The increment used (Δx_i) should therefore be as small as practical and certainly no larger than the uncertainty in the parameter x_i. However, a complication can arise if the increment is so small as to result in changes in the calculated result, y, that are comparable with the resolution of the calculator or computer spreadsheet; in these circumstances the calculation of c_i can become unstable. The problem can be avoided by starting with a value of Δx_i equal to the uncertainty in x_i and progressively reducing Δx_I until the value of c_i agrees with the previous result within a suitable tolerance. This iteration process can, of course, be automated within a spreadsheet such as Excel.

B1.4 Combination of Uncertainties

Once the standard uncertainties of the input quantities and their associated sensitivity coefficients have been determined from either Type A or Type B evaluations, the overall uncertainty of the output quantity may be determined from

$$u_c(y) = \sqrt{\sum_{i=1}^{N}(c_i u(x_i))^2} \qquad [B.20]$$

Where relative uncertainties have been used, relative sensitivity coefficients must also be used, where

$$u_c^*(y) = \sqrt{\sum_{i=1}^{N}(c_i^* u^*(x_i))^2} \qquad [B.21]$$

The above equations assume that the individual input quantities are un-correlated, the treatment of correlated uncertainties is more complex and is discussed in Ref 1.

B1.5 Expanded Uncertainty

The expanded uncertainty, U, is calculated by multiplying the combined standard uncertainty, U_c, by a coverage factor, k.

APPENDIX C

UNCERTAINTY ANALYSIS EXAMPLE: UNCERTAINTY IN THE MASS BALANCE AT A WATER TREATMENT WORKS

APPENDIX C –

UNCERTAINTY ANALYSIS EXAMPLE: UNCERTAINTY IN THE MASS BALANCE AT A WATER TREATMENT WORKS

UNCERTAINTY EXAMPLE

In order to provide an example of how an uncertainty analyses is carried out, the following hypothetical scenario has been developed. This scenario is not based on a real situation and the uncertainty estimates are for illustrative purposes only. It is therefore explicitly expressed that the various uncertainty assumptions in this example should not be viewed as fact; it should be remembered when conducting an uncertainty analyses that all specific aspects of a particular application are required to be examined and accounted for.

THE PROCESS

A 16 inch electromagnetic meter measures water output from a reservoir to a treatment works. A 12 inch meter measures the output from the treatment works to the distribution network. The treatment works also uses water in the process and although it is used in an intermittent way, it is discharged to a settling pond. The relatively constant flow from the pond is measured using a V-notch weir. Figure 1 illustrates the process.

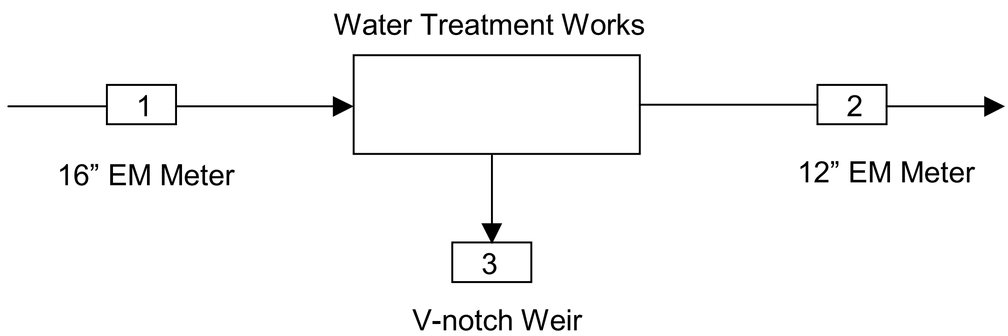


Figure 1 Water Treatment Works

There is a concern with the water balance in the system indicating a potential leak. If there was no leak, the difference between the input and output to the works (meters 1 and 2 respectively) should be equivalent to the water being discharged through the weir to the pond.

A comparison between the uncertainty in the meter difference and the weir discharge has to be estimated in order to establish whether a leak is likely or whether a poor comparison could be accounted for in the uncertainty of the measurements.

OVERVIEW OF EXERCISE

This example is divided into 2 main parts. Firstly, an uncertainty analysis of the input and output meters is performed, including an uncertainty assessment of the difference between these measurements. Secondly, an uncertainty analysis of the weir is performed and an uncertainty assessment is made of the weir flow measurement. These are then compared and overall conclusions established.

UNCERTAINTY ANALYSIS OF METERS 1 AND 2

The uncertainty analysis is now performed following through four separate steps. Each of these is now described in detail.

Step 1 Identify What Measurements Are To Be Used

It may be obvious, but it has to be established what measurements are to be used. This will establish the definition of the uncertainty that is being estimated. For the purposes of water balance or leak detection, a number of different tests could be applied:

a) Short time period measurement, overnight, at low demand, and when the works has constant through flow and internal processes are closed down.

b) A longer time period, overnight, with low demand but with the internal process working.

c) A measurement over an entire 24 hour period. Or the mean of a number of days.

d) A measurement based on an average weekly or monthly consumption.

It is not the place for this example to recommend a best method; depending on the specific uncertainty that is being examined, any one of the above could be appropriate. In this example a measurement of the monthly total is used.

Step 2 List The Sources Of Uncertainty In The Process

The second stage in the analysis is to list all potential sources of uncertainty in each measurement. The list, detailed in Table C.1, should include every possible uncertainty source and nothing, however unlikely, should be discounted. Comments and descriptions are added to the list to document the process and justify later decisions.

Table C.1 List of Uncertainties in the Metering

Uncertainty	Applies to	Comments
Manufacturers uncertainty (high flow to 10% span)	Meter 1 and 2	Basic uncertainty expected from manufacturer data and knowledge of similar meters.
Manufacturers uncertainty (Low flow 10% to 1% and below 1% of span1)	Meter 1 and 2	Increased uncertainty while the meter is running below the rated minimum. Two levels of performance can be expected
Potential ageing uncertainty.	Meter 1 and 2	Lack of confidence as the meter gets older.

Effect of installation	Meter 1 and 2	Upstream flow conditions may affect the meter.
Uncertainty of calibration or verification	Meter 1 and 2	The meters are calibrated, in this case by insertion meter, at one (high) flowrate.
Difference from verification (Tolerance)	Meter 1 and 2	This reflects the difference between the reading and the calibration value. This is treated differently depending if the error is used to correct the reading or only to establish verification within a tolerance.
Measurement sample times etc	Meter 1 and 2	This is not an issue in this case as monthly totals are being used.

Step 3 Lay Out An Uncertainty Table And Estimate Uncertainties

At this stage an uncertainty analyses is best performed on a spreadsheet. In this example there are two main measurements; meter 1 and meter 2. At this stage we can consider these to be two independent measurements. We will therefore work with meter 1 first.

Two uncertainty sources apply to the use of the meters at low velocities. For this reason a preliminary task has to be carried out. The quantity of water used with the meters working at low and very low velocity has to be estimated to allow the low velocity uncertainties to be estimated as part of the total.

Table C.2 Breakdown of Meter Velocity Bands for Each Meter

			Meter 1	Meter 2
Approx time /day in 1 -10%		Hours	12	6
Approx time /day below 1%		Hours	7	4
Approx vol /month in 1 - 10%		m3	180000	50000
Approx vol/month below 1%		m3	7500	1500
Approx vol/month in 10 - 100%		m3	87660	196144
Total		m3	275160	247644

The most robust methodology for uncertainty analyses is based on using absolute values of volume (m^3). Using relative uncertainties, based on percentages, can give rise to significant mistakes when more complex examples are analysed such as the weir analysis (described later) or if temperature is an influence. Although the relative uncertainties could have been used in this case, this example uses the absolute values of volume instead. Here, where an uncertainty is expressed as a relative (%) value, the absolute figure is calculated and this used throughout the analysis. Throughout this analysis all the sources of uncertainty are being expressed in terms of volume and for this reason the sensitivity factor for each is unity.

The applicability of each uncertainty listed in Table C.1 is now discussed and the reason for including or excluding the source is detailed.

If the meters 1 and 2 had not been verified, (in this example with an insertion probe), then a number of uncertainties would exist including: basic meter uncertainty, ageing effects and the effect of the installation. Since a calibration has been performed with a probe, the calibration uncertainty takes precedence over these other sources of uncertainty.

As the meter was only calibrated at one flowrate within the upper range of the meter, the increased uncertainty of the meter at other (lower) flowrates has to be retained.

The uncertainty arising from the calibration result has to be included. It is here that the calibration result is used to determine if the meter error lies within an acceptable tolerance, and subsequent meter readings are uncorrected for any calibration error. In this case, the tolerance should be used as an uncertainty source with a rectangular distribution. If the meter reading is corrected for the error shown by the calibration no additional uncertainty would be added.

The above discussion illustrates the complexities that arise when performing an uncertainty analysis and demonstrates the need to specify, justify and document the rationale for the various sources of uncertainty included in the analysis. Uncertainty analysis is therefore summarised as not purely being just about statistics and mathematics, but involves a considerable amount of thought, consideration and honesty. It is vital that this reasoning be documented.

Table C.3 Uncertainty in Meter 1

Uncertainty in	Monthly Quantity		Value	275160	m3		
Source (1)	Expanded uncertainty % (2)	m^3 (3)	Probability distribution (4)	Divisor (5)	Sensitivity Coefficient (6)	Standard uncertainty (7)	Standard Uncertainty Squared (8)
Meter 1							
Uncertainty at High Flow	0	0	Rect	1.732	1	0.0000	0.00E+00
Uncertainty at <10%	1	1800	Rect	1.732	1	1039.23	1.08E+06
Uncertainty at <1%	10	750	Rect	1.732	1	433.01	1.88E+05
Calibration	3.71	10213.51	Normal.	2	1	5106.75	2.61E+07
Calibration error (Tolerance)	2	5503.2	Rect	1.732	1	3177.27	1.01E+07
Ageing	0	0	Rect	1.732	1		
Installation	0	0	Rect	1.732	1		
Combined uncertainty	4.45%	12237.89	Normal	2	1	6118.94	3.74E+07

Table C.3 shows the uncertainties in 'Meter 1' in a spreadsheet format. The standard uncertainty (7) is calculated by multiplying the volumetric uncertainty (3) by the sensitivity coefficient (6) and dividing by the appropriate probability divisor value (5) [normal $\Rightarrow$ k=2, rectangular $\Rightarrow$ k=1.73]. The uncertainties are then added by root sum square addition whereby each standard uncertainty is squared and the column summed. It is at this stage that the uncertainties show clearly which sources contribute the largest uncertainty and hence which need particular attention when the process is to be improved.

The combined uncertainty for the meter is calculated in the bottom line of Table C.3 and the calculation sequence should be read from right to left. The sum of the standard uncertainty squared values is 'square rooted' and multiplied by the coverage factor (see below). This gives the combined uncertainty expressed in m^3 which is then converted into a percentage of the total (=275,160). It should be noted that there is no need to be concerned about applying a sensitivity coefficient in the calculation of combined uncertainty as this has to be equal to unity. In this example, a normal distribution for the probability distribution of the combined uncertainty has been assumed resulting in application of a coverage factor of k=2. For a normal distribution this coverage factor approximates to a confidence level of 95%.

Step 4 Correlation

The final assessment to be made is an examination of the difference between the readings from meters 1 and 2.

Some uncertainty sources may be common, i.e. correlated, between the two meters. In this example there are two meters of different sizes, in different locations. This suggests that the behaviour of these meters is uncorrelated. They have however been calibrated by the same operator using the same equipment and at the same approximate time. It is clear that the calibration uncertainty will contain aspects which are correlated. To be performed now is a breakdown of the sources of uncertainty in the calibration into correlated and uncorrelated parts.

Table C.4 Calibration Uncertainties

Uncertainty in	Calibration			Correlated		Un-correlated	
Source	Expanded uncertainty %	Probability distribution	Divisor	Standard uncertainty	Standard Uncertainty Squared	Standard uncertainty	Standard Uncertainty Squared
Calibration of equipment	2	Normal.	2	1.000	1.00		0.00
Probe Placement	2	Rect	1.732	0.577	0.33	0.577	0.33
Repeatability	1.155	Rect	1.732		0.00	0.667	0.44
Flow profile	2	Rect	1.732		0.00	1.155	1.33
Combined uncertainty	3.71	Normal	2	1.155	1.33	1.453	2.11

Firstly, a useful technique to carry out is a separate analysis of various parts of a process and compile these into a final results table. This is illustrated in Table C.4 for the calibration, but may also apply to any specific measurement which may have many uncertainty sources. Note, the combined uncertainty value for the calibration in Table C.4 is calculated to be 3.71 and it is this value that has been entered in the overall meter uncertainty calculation in Table C.3. It is further noted that the data presented in Table C.4 are in the form of relative uncertainties (%).

Secondly, the calibration result was derived from the mean of a number (n) of repeat measurements. Where the number is large, say of the order of 10 or more, the uncertainty of the mean is given by dividing the 'standard deviation' by $\sqrt{n}$. Where there are far fewer repeat results, say just 2 or 3, this approach should be avoided. The danger here is that a small number of results may indicate an unrepresentative repeatability. If one more result was obtained it could be significantly different indicating the true spread of the repeatability. In such a case, a historical assessment of many repeat data could be performed in order to establish the tolerance level within which the vast majority (say 95%) of measurements lie. The uncertainty of the mean in this case is then given by dividing the tolerance interval by $\sqrt{n}$. Such procedures are common in the oil industry whereby repeating a measurement 10 times or more is regarded simply as impractical.

In this example the following assumptions have been made: (1) the traceability of the equipment is correlated since the same insertion probe is used on both meters, (2) the repeatability is un-correlated since meters 1 and 2 are measuring different flows, (3) the flow profile uncertainty is un-correlated since the meters are installed at different installations, and (4) the probe installation (alignment, measuring practices, etc.) is partially correlated - although the probe is used at two different locations, the results will be influenced to a degree by operator technique.

The procedure of apportioning a partially-correlated uncertainty (to correlated and un-correlated) is very much down to issues of judgement. In this example it is assumed that both the correlated and un-correlated portions have equal weighting. Here, the probe installation expanded uncertainty of 2% is divided by the divisor of 1.732 (rectangular distribution) to give 1.155. Since equal weighting is assumed, 0.577 is attributed to the correlated and un-correlated parts of the calculation. In this example, if a different weighting was to be assumed, the procedure would be simply to apportion the total (1.155) in whatever ratio was considered appropriate.

Table C.3 is now re-calculated, as shown in Table C.5, separating the correlated and uncorrelated items.

Assessment

From perusal of the Meter 1 combined uncertainties and the Meter 2 combined uncertainties (Tables C.5 and C.6), it is noted that for the same input figures, the uncertainties are almost the same. Meter 1, being larger (16-inch), incurs larger uncertainties at low velocities but because the total volume passed at low flowrates is small, the difference between the two meters is marginal. This, in retrospect, shows that such a detailed examination of the flowrates with time was not required. However, this result can only be found out if a detailed examination is carried out. If however only night flows were used, the uncertainty would not only be larger but the difference between the meters would be much more pronounced.

Table C.5 Uncertainty in Meter 1 Showing Correlation

Uncertainty in	Monthly Quantity		Value	275160	m3	Correlated		Un-correlated	
Source	Expanded uncertainty %	m3	Probability distribution	Divisor	Sensitivity Coefficient	Standard uncertainty	Standard Uncertainty Squared	Standard uncertainty	Standard Uncertainty Squared
Meter 1									
Uncertainty at <10%	1	1800	Rect	1.732	1		0.00E+00	1039.23	1.08E+06
Uncertainty at <1%	10	750	Rect	1.732	1		0.00E+00	433.013	1.88E+05
Calibration	1.155	2860	Standard	1	1	2860	8.18E+06		
	1.453	3998	Standard	1	1			3997.98	1.60E+07
Calibration error (Tolerance)	2	5503	Rect	1.732	1		0.00E+00	3177.27	1.01E+07
Combined uncertainty	**4.33**	1.19E+04	Normal	2	1	2859.55	**8.18E+06**	5229.38	**2.73E+07**

Similarly, the whole process is repeated for meter 2 (see Table C.6)

Table C.6 Uncertainty in Meter 2 Showing Correlation

Uncertainty in	Monthly Quantity		Value	247644	m3	Correlated		Uncorrelated	
Source	Expanded uncertainty		Probability distribution	Divisor	Sensitivity Coefficiant	Standard uncertainty	Standard Uncertainty Squared	Standard uncertainty	Standard Uncertainty Squared
	%	m3							
Meter 2									
Uncertainty at <10%	1	500	Rect	1.732	1			289	8.33E+04
Uncertainty at <1%	10	150	Rect	1.732	1			87	7.50E+03
Calibration	1.155	2860	Standard	1	1	2860	8.18E+06		
	1.453	3598	Standard	1	1			3598	1.29E+07
Calibration error (Tolerance)	2	4952.88	Rect	1.732	1			2860	8.18E+06
Combined uncertainty	**4.38**	1.08E+04	Normal	2	1	2860	**8.18E+06**	4606	**2.12E+07**

The final stage in this assessment is to combine the uncertainties in meter 1 and meter 2 to calculate the uncertainty in the difference. This analysis is summarised in Table C.7 where the following procedures have been implemented:

- Sensitivity coefficients are defined.
- Correlated standard uncertainties are added arithmetically.
- Un-correlated standard uncertainties are added by root sum square method.
- The two total uncertainties are then added by root sum square.
- The final total is multiplied by the appropriate coverage factor (k=2) and rounded up.
- Uncertainty is expressed as a percentage of the difference between the two meters.
- The final measurement statement is formulated.

Table C.7 Uncertainty in Volume Difference Uncertainty in Discharge

		Vol Diff 27516 m^3				
Source	Sensitivity	Standard uncertainties			Uncertainty @k=2	
		Correlated	Uncorrelated	Total		
		Uncert * Sens	Uncert * Sens			
		m^3	m^3	m^3	m^3	%
Meter 1	1	2860	5229			
Meter 2	-1	-2860	4606			
Difference		0	6969	6969	13937	50.7
		Arithmetic Sum	Root Sum Square			

Conclusion from Uncertainty Analysis - Measurement Statement

The difference between the measured volumes entering and leaving the treatment works is 27,516 m^3 (275,160 – 247,644) with an estimated uncertainty of $\pm$ 13,937 m^3 (51%). This assumes a coverage factor of k=2, which approximates to a 95% confidence level.

MEASUREMENT OF WATER DISCHARGED FROM THE TREATMENT WORKS

In this example the amount of water used in the works is assumed to be equivalent to the water passing through the 'v-notch' weir. If there are no leaks at the site, then the difference in the readings of meters 1 and 2 should be approximately equal to the volume measured by the weir.

Developing the Example

Over the same month as examined earlier, the monthly flow measured by the weir is assumed to be exactly 10,000 m^3. This is less than the difference between meters 1 and 2 of 27,516 m^3 suggesting there is unaccounted for water, possibly a leak of 17,516 m^3 at the site.

From the work earlier, it has been established that the uncertainty in the difference between the two meters is $\pm$ 13,937 m^3. In other words, the difference, (to a 95% level of confidence), is expected to lie within the range of 13,579 to 41,453 m^3. Since the weir flow (10,000 m^3) is outside this range there is an even stronger suggestion that there may be a leak at the site. However, still to be determined is the uncertainty associated with the weir flow measurement. If this measurement is shown to have a low uncertainty, say $\pm$ 1,000 m^3, then it would be concluded that there is more than likely a leak since the weir flow of 9,000 to 11,000 m^3 is still short of the difference measurement (13,579 to 41,453 m^3). On the other hand, if the uncertainty in the weir flow is shown to be high, say $\pm$ 5,000 m^3, the weir flow of 5,000 to 15,000 m^3 is now within the difference measurement (13,579 to 41,453 m^3). In such a case it would be concluded that the difference between meters 1 and 2, in comparison to the weir flow, is within the uncertainty of the measurements. Although a leak at the site cannot be ruled-out, it is not sufficiently severe to be highlighted as probable.

Continuation of Uncertainty Analysis

In the following continuation of the example it is assumed that an uncertainty analysis, (similar to the ones carried out for meters 1 and 2), has been performed on the v-notch weir. The flowrate of water passing through the weir is described by the relationship:

$$Q = C_e \frac{5}{15} \tan\frac{\alpha}{2} \sqrt{2g_n}\, h_e^{5/2} \quad \text{........ (Equation C.1)}$$

where,

Q	flowrate (m^3/s)
C_e	coefficient of discharge
α	notch angle (degrees)
h_e	effective head (m)
g_n	gravitational constant (m/s^2)

Three sources of uncertainty are assumed to affect the accuracy of the measurement: the discharge coefficient, the v-notch angle, and the height measurement. The assumption is made that the uncertainty of time measurement and the gravitational constant are insignificant.

As shown in Table C.8 it is assumed that the following expanded uncertainties (95% confidence) have been established:

- discharge coefficient (C_e) = 0.586 $\pm$ 3% $\Rightarrow$ 0.586 $\pm$ 0.0176
- v-notch angle (α) = 90^o $\pm$ 1^o
- height (h_e) = 0.115*m $\pm$ 0.005 m

* The value of 0.115 metres has been calculated using Equation C.1 - this is the value of h_e which, with the other given parameters, results in a total monthly flow of 10,000 m^3.

This spreadsheet table can therefore be used to illustrate the sensitivity of the measurement to the various factors. In other words, the affect of changing, for example, the uncertainty in the height measurement can be compared against changing the uncertainty in the v-notch angle. This allows an informed judgement to be made on the level of uncertainty that is required with the various measurements in order to attain a given level of combined uncertainty.

Sensitivity Factor

It is insufficient to consider only the magnitudes of component uncertainties in input quantities, it is also necessary to consider the effect each input quantity has on the final result. Examining Equation C.1, for example, it is clear that there is not a linear relationship between flowrate (Q) and effective head (h_e); flowrate is proportional to $(h_e)^{5/2}$. To illustrate this, consider the effect of doubling the effective head. All other things be equal, this would result in flowrate increasing by a factor of 5.66. The 'Sensitivity Factor' is used to relate the uncertainty in a measurement to the uncertainty in the final result.

The sensitivity factor can be obtained by one of two ways:

a) Partial differentiation of the equation with respect to each parameter in turn. The values of each parameter are substituted and the sensitivity factor calculated.

b) Establish the difference between the calculated flowrate when measured firstly by applying the measured values and secondly by applying the same values but incremented by a chosen amount. The sensitivity factor is this difference divided by the increment. For most applications the increment should be equal to the uncertainty in the parameter. Choosing the incorrect increment can give rise to serious numerical errors.

In this example, detailed in Table C.8, the second method has been applied since it is particularly well suited to a spreadsheet approach. It is also the preferred option for engineers who are less practised in the art of differentiating complex functions.

Detailed below is an example of how the sensitivity coefficient is calculated for the discharge coefficient, C_e. NB – in the spreadsheet, a function has been written to perform these automatically.

Using Equation C.1, when C_e = 0.586, A =90^o, g_n = 9.81, h_e = 0.114735, the flowrate solution, Q = 0.00386 m^3/s. Since the uncertainty analysis is being performed over a full month, this represents a flow over the month of 0.00386 x 30 days x 24 hours x 3,600 s = 10,000 m^3. C_e is now incremented by the expanded uncertainty value (0.0176) to give C_e = 0.6033. Using the same values for the other variables described above, the flowrate solution is Q = 0.00397m^3/s. This is equivalent to a flow over the month of 10,300 m^3. Taking the difference between 10,300 and 10,000 gives 300 m^3. The sensitivity coefficient is given by dividing this value by the increment (0.0176) giving 17,065 as detailed in Table C.8.

Table C.8 Uncertainty of V-notch weir

Uncertainty in	Monthly Vol			Value	10000		m3		
Source	Value	Expanded uncertainty		Probability distribution	Divisor	Incr.	Sensitivity Coefficient	Standard uncertainty	Standard Uncertainty Squared
		%	Units						
Uncertainty in C_e	0.586	3	0.0176	Rect	1.73	0.0176	17065	173.21	3.00E+04
Uncertainty in Angle	90	---	1	Rect	1.73	1.0000	176	101.66	1.03E+04
Uncertainty in height	0.11473	----	0.005	Rect	1.73	0.0050	225067	649.71	4.22E+05
G	9.81	0	0	Normal.	1	0			0.00E+00
Time	30 Days	0	0						
Combined uncertainty		**13.6**	1360.1	Normal	2		1	680.04	4.62E+05

Conclusion from V-notch Uncertainty Analysis – Measurement Statement

The v-notch flow measurement of 10,000 m^3, has an estimated uncertainty of $\pm$ 13.6% (1,360 m^3). This assumes a coverage factor of k=2, which approximates to a 95% confidence level.

OVERALL CONCLUSIONS

As detailed at the start of this Appendix, the purpose of this example is to determine if a leak is likely to be present at the site or whether a poor comparison between the difference measurement of meters 1 and 2 and the weir measurement could be accounted for in the uncertainty of the measurements.

It has been established that the difference between meters 1 and 2 is likely to lie within the range of 13,579 to 41,453 m^3. From the assessment of the uncertainty in the weir measurement it has been established that the measurement of 10,000 m^3 is within $\pm$ 13.6%. Therefore, the weir volume is likely to be within a range of 8,640 to 11,360 m^3. Since the range of the weir measurement does not overlap with the range of the meter difference measurement, it is concluded that there is likely to be a leak at this site, whereby water is being lost from the system that is not being accounted for.

APPENDIX D

CASE STUDY REPORT: UNCERTAINTIES ASSOCIATED WITH INSERTION PROBES

EXECUTIVE SUMMARY – APPENDIX D

This report identifies and describes the sources of uncertainty that are associated with the application of insertion flow meters. A number of these sources of uncertainty are investigated with the aim of providing the information required to help informed decisions to be made regarding both the use of the measuring instrument itself and operating procedures.

Throughout these investigations extensive use is made of mathematically derived flow profiles. The reason for this is that these have a known exact solution (mean flow rate) and thus allow the corresponding errors to be quantified. These profiles are considered to be similar to those experienced in practice but it is acknowledged that they will not be identical. It is therefore stressed that although a number of errors have been quantified in this report these should not be considered to be absolute. Instead, these errors should serve as an indication of the severity of the various effects.

The first investigation shows that the most critical source of uncertainty in the application of insertion probes is installation effects, particularly where a D/8 position is assumed to correspond to the mean flow rate. A severely distorted flow profile, similar to that which might be experienced just downstream of a gate valve which has not been fully closed, is investigated in order to quantify the errors that could result if (1) single D/8 positions are assumed, (2) a single vertical or horizontal traverse is performed, and (3) both a vertical and horizontal traverse are performed. Here, in this example, it is shown that if D/8 positions are used then errors could be as high as -88 to 118%. Single vertical traverse gives an error of 8.4% whereas a single horizontal traverse gives an error of -5.9%. The advantage of taking both vertical and horizontal traverses is indicated by the much smaller error of just 1.3%.

The second investigation aims to quantify the errors introduced into the integration when the probe has been misaligned in the pipe. Here, a mathematically produced fully developed flow profile is assessed for misalignment angles of 5, 10, 15, and 20°. The results from this analysis indicate that errors of -0.16, -0.63, -1.37 and –2.38% are produced respectively.

The last investigation concentrates on two sources of uncertainty that are associated with the method-of-cubics integration technique. Firstly, the errors arising from performing 7, 9, 11 or 13 traversing points are quantified. Secondly, the uncertainties associated with assuming a constant Von Karman coefficient of m = 7 in the integration formula are quantified. From the analysis of a fully developed mathematical profile it is estimated that the following errors are introduced when a 7, 9, 11 or 13 traversing point traverse is performed respectively: 0.31, 0.19, 0.13 and 0.10%. This means, for example, that if 7 pairs of equally spaced velocity and depth measurements are taken across a traverse, and the velocity profile is fully developed and all readings (depth and velocity) are 100% accurate, the calculated mean flow rate using the method-of-cubics integration would still be in error by 0.31%.

The results from the analysis into the assumption of a constant Von Karman coefficient, m = 7 are detailed. Here, if m values in the range of 6.6 to 7.6 are considered, it is shown that the maximum error (with a 7-point traverse) is in the order of 0.27 to -0.34%.

CONTENTS

D.1 INTRODUCTION

Insertion probes (insertion flowmeters) are widely used in the water industry as a means of measuring flowrate in pipes. In applications where there is no permanently installed flowmeter, particularly in large diameter pipelines, they provide a low cost alternative to full bore meters. Insertion probes are also becoming increasingly utilised, especially by the water industry, as a means of verifying the performance of permanently installed meters.

Even when the accuracy of a brand new full bore meter is assumed to be within the uncertainty stated by the manufacturer, a number of factors can influence the performance of the meter once it has been installed. These include: damage during installation, incorrect meter set up, wear, drift and inappropriate flow conditions (installation effects). The ability therefore to verify the performance of a meter in-situ, without the need to remove the meter and have it tested elsewhere, is extremely attractive. In some applications, such as at reservoirs outlet installations, there may simply be no potential for removal of the meter without causing major disruption and inconvenience to customers. Insertion probes provide a cost-effective means for such for verifying meters.

Probes, however, have the major disadvantage over full bore meters that they can only provide a flowrate based on a velocity measurement at the single point where the probe is inserted into the flow. In order to obtain the flowrate through a pipe with better accuracy the probe has to be inserted to various depths across a diameter of the pipe and measurements of velocity made at each point. This resulting velocity and depth information provides the flow profile and is integrated to provide the required mean flowrate solution.

The funding for this research was provided by the UK's Department of Trade and Industry through the NMSPU (National Measurement System Policy Unit) 1999-2002 Flow Programme, together with co-funding from a number of water companies: Anglian Water, Dwr Cymru, Northumbrian Water, Southern Water, Thames Water and Yorkshire Water. The major advantage to be gained from this collaboration with the water companies is the direction and support they have provided, ensuring that the research is carried out with a focus on issues of particular industrial relevance. A major part of this project was to undertake a number of case studies and this report presents the findings from one such study carried out for one of the water companies.

D.1.1 Overview of this Report

The accurate determination of mean flowrate using insertion probes is appreciated as not being a trivial exercise, and, as with any flow measurement technique, there are sources of uncertainty associated with the application of insertion flowmeters. This report aims to identify and describe these sources of uncertainty and investigate a number of them. These investigations aim to quantify the extent to which various factors may affect the probe measurement readings, allowing informed decisions to be made regarding both the use of the measuring instrument itself and operating procedures.

A list of the uncertainties associated with the application of insertion probes is provided in Sections D.2.1 and D.2.2. Following this, the main conclusions from three separate areas of investigation are presented. The methodology, analysis and results from each of these investigations are provided separately in appendices D1, D2 and D3.

The first investigation (Appendix D1) looks at an example of an installation effect where the insertion probe technique is applied to a severely disturbed flow profile which has been constructed using a mathematical formula. This approach has been used as the formula has a known exact solution (mean flow rate) allowing the corresponding errors to be quantified. Although this artificial profile does not aim to model any particular design of installation accurately this example does illustrate the magnitude of the errors that could be expected with such a severely distorted profile. In this example the following measurements are compared: single point measurements at D/8, a single 7-point traverse, two perpendicular 7-point traverses.

The second part of the investigation (Appendix D2) addresses the uncertainties that can be introduced by misalignment of the measuring probe. Here, the welded boss on the outside of the pipe is assumed to have been misaligned resulting in the probe being entered across the flow on a traverse that is not across the true diameter of the pipe. A number of misalignment angles are considered (5, 10, 15 and 20°) and the resulting errors from a 7-point traverse across a fully developed profile are calculated.

In the third investigation (Appendix D3), the errors associated with the integration formula are quantified. First of all it is established, using a fully developed flow profile model, that if a very large number of traversing points (100) is assumed then this error approaches zero. Since such a large number of points is clearly impractical the errors resulting from taking just 7, 9, 11 and 13 points across the same virtual profile are quantified. This allows a judgement to be made with regards to the benefits (in terms of uncertainty), for example, of performing a 9-point traverse compared with a 7-point traverse. This part of the investigation concludes with a quantification of the errors introduced by the assumption in the integration formula that the velocity profile is unaffected by Reynolds number.

D.1.2 Insertion (Probe) Flowmeters

Insertion flowmeters, as the name suggests, are inserted into the flow, and measure the local fluid velocity at the location of the meter sensor. The mean flow velocity in the pipe can be approximated from a single point velocity at the D/8 position if a fully developed flow is assumed (Section D1.1.1). Alternatively, a number of point velocity readings can be taken across a traverse of the pipe, and these data integrated to generate the mean velocity (Section D1.1.3).

The general form of insertion meter design is to have the sensing head fixed onto the end of a rod which passes through a support housing into the pipe. In closed pipe water flow measurements this sensing element is typically an external electromagnetic meter, an internal electromagnetic meter or a turbine meter. Tests at NEL in 1996 on the effects of installation effects on insertion meters concluded that the external electromagnetic meter was superior to both the internal electromagnetic meter and the turbine insertion meter[1].

The *Aquaprobe* is a type of external electromagnetic insertion meter manufactured by ABB and is widely used in the water industry. This instrument is now supplied with built-in data collection and analysis software allowing a quick and user-friendly means of determining flowrate. As such devices become increasingly automated, there is a danger that the users of such equipment do not fully recognise and appreciate the sources of uncertainty associated with the probe measuring technique; it is therefore worthwhile summarising these sources of uncertainty. This will allow informed decisions to be made regarding both the use of the measuring instrument itself and operating procedures.

D.2 SOURCES OF UNCERTAINTY ASSOCIATED WITH INSERTION PROBES

D.2.1 Point Velocity Uncertainties

The following is a list of sources of uncertainty that are associated with the measurement of a point velocity using an insertion meter:

- Uncertainty in the Insertion Meter Calibration – as with all types of measurement, no result indicated by an instrument is exact. Even when the meter is calibrated to the best national or international standards there is still an uncertainty associated with how close the measurement of the instrument is to the truth. The uncertainty associated with any measurement can never be better than that associated with the calibration itself.

- Insertion Blockage Factor –the sensing element of the probe is attached to the end of a rod, which is entered into the flow. This causes a blockage as the flow has to pass round the obstruction, resulting in a slightly increased flow velocity due to the reduction in effective cross sectional area. This effect must be allowed for and is more significant in smaller diameter pipes and with greater insertion depths. Typically, blockage factor corrections are made automatically by the probe software when the likes of the Aquaprobe is used. There is however a level of uncertainty associated with this correction.

- Velocity Profile Factors – one common method for determining mean flowrates using insertion probes is to enter the probe to a given position, for example, the centreline, and apply a velocity profile factor to this reading. There is clearly an uncertainty in applying such a velocity profile factor. The velocity profile may also change with flowrate, particularly where there is a transition from turbulent to laminar flow or installation effects introduce flow disturbances such as asymmetry and swirl. Such factors will increase the uncertainty associated with the application of a velocity profile factor.

- Velocity Profile Local to the Measuring Probe – the sensing head on a probe does not measure the velocity at an infinitely small point but instead contributions to the signal are made from a small area of the flow. At the centre of a fully developed flow, the flow velocity at all points passing the sensing head could essentially be considered to be the same. However, near the pipe wall, the flow velocity reduces due to friction and the flow passing the sensing head cannot be assumed to have the same flow velocity at all points. Therefore, there is an uncertainty associated with the velocity profile local to the probe.

- Alignment of Probe Head to Flow Direction – the alignment of the small gap in the sensing head to the flow is clearly important. The probe must be rotated so that the flow direction is as square as possible to the small gap in the sensing head. This is achieved in practice by aligning the cross bar used to manoeuvre the probe with the direction of the pipework.

- Insertion Depth and Angle – a critical measurement to be made when performing any probe measurement is the precise location to which the probe is inserted. If, for example, the probe is to be inserted to the centre of the pipe and a velocity profile factor applied to calculate the mean flow, it is clear that there is an uncertainty associated with how close the sensing head is located to the precise centre of the pipe. In addition, the axis of the probe traverse must be aligned with the pipe centre; any angular error in fixing the traverse mechanism to the pipe wall will result in this axis missing the centre and will lead to errors in the measured insertion depth.

- Flow Velocity – when an insertion meter is calibrated it is likely to be tested only at one or two flow velocities. The application of the instrument to measure a flow velocity which is different from that in which it has been calibrated will introduce an associated uncertainty. If the flow velocity is reasonably high, particularly in large diameter pipes, then there is the potential for the entire flow measuring assembly to vibrate. In such conditions further uncertainty is introduced. If a probe traverse is not possible due to this vibration problem then it might be assumed that the D/8 position approximates to the mean flowrate. High uncertainties are associated with such an approximation, particularly in installations where the flow profile is not fully developed or is axisymmetric.

- Duration of Measurements/Sample Frequency – even when the mean flowrate through a pipe is constant, the velocity at a given point in the flow will be varying with time. Factors which can contribute to such transient fluctuations are installation effects (which can introduce asymmetry and swirl) and the degree of turbulence (Reynolds number effect). It is therefore important when the velocity at a point is measured using an insertion probe that a sufficient length of time and a sufficiently high sampling frequency are used to give a representative average signal.

- Unsteady Flow/Pulsations – where the mean flowrate is changing with time (for example with a demand-dependent reservoir outlet supply) there is an uncertainty introduced, since, as described above, the measurement is required to be established over a sufficient sampling time. Even in conditions where the mean flowrate is constant, there are installation effects which can cause severe transient effects resulting in the flow velocity at a point varying quite considerably with time. This type of uncertainty is also introduced in situations where the flow may be pulsating, due, for example, to the application of a pump in the system.

- Temperature – changes in the temperature of the fluid being measured will have an effect on the operation of the instrument. Expansion/contraction effects in the rod or sensing element casing are also possible.

D.2.2 Velocity Uncertainties when Traversing

When insertion meters are traversed across the flow, and the data integrated to determine a mean flow velocity, additional sources of uncertainty have to be taken into consideration:

- Internal Pipe Diameter, Pipe Cross-sectional Area and Pipe Ovality – the measurement of the cross-sectional area of the pipe is absolutely critical to the calculation of volumetric flowrate. Uncertainties in the measurement of diameter arise from probe alignment and the measurement instrument itself. In addition, pipe ovality can lead to significant errors when the area is derived from a single diameter measurement.

- Wall Condition Inside the Pipe – poor wall conditions, such as encrustation or corrosion will result in an irregular (un-smooth) surface. This has implications not only for diameter measurements but also for the flow profile, including the possibility of localised flow disturbances close to the pipewall.

- Alignment of Probe to Wall – a traverse must be across a diameter of the pipe. If the welded boss has not been set square to the pipe then the probe will be entered at an angle and will therefore not be on the diameter. The implications of this are that not only would any diameter measurement be incorrect, but the velocity information obtained would be associated with incorrectly detailed positions.

- Number of Traverses – a traverse is principally performed in order to deduce the mean flow rate passing through the pipe. In addition, a traverse is often used to establish the insertion depth for the probe to measure the mean flow rate directly. However, performing a single traverse gives no information on the variability of the mean flow position with flowrate. This can be rectified by repeating the traverse at a number of flowrates and comparing the results. Another very useful exercise with repeat traverse information is to compare the velocity profiles at a fixed flowrate. If the repeatability of the velocity profile shape is poor, this will result in a higher uncertainty.

- Number of Traverse Directions – probe tapping point(s) are typically set up to allow either (1) a single vertical or horizontal traverse, or (2) a pair of traverses at 90 degrees to one another. If the flow conditions are known to be perfectly well developed then, in theory, there is no benefit (other than described above) from performing more than a single traverse. The reason for this is that the flow is axisymmetric which means that for any insertion depth on any circumference position of the traverse, the measured velocity is the same. Such ideal conditions are however seldom available and substantial benefits, in terms of reduced uncertainty, can be obtained if traverses are performed on two different directions. Performing traverses on more than two different directions is clearly the ideal but unlikely to be conducted in practice because of the cost.

- Number of Point Velocities Measured on Each Traverse – the principal purpose of performing a traverse is to understand the flow profile and so calculate the mean flowrate passing through the pipe. Clearly, the greater the number of points measured, the more accurate will be the calculation.

- Proximity of Pipe Wall – as the pipe wall is approached, the velocity profile changes become more and more acute. This was discussed in Section D.2.1 with reference to the uncertainty associated with the 'Velocity Profile Local to the Measuring Probe'. As well as this uncertainty, there is also an uncertainty introduced if the probe proximity to the pipewall is so close that there are resulting interaction effects between the pipewall and sensor.

- Flow Changes During Traverse – during any insertion probe measurement the ideal situation is where the pipework system is known to have a steady unchanging flowrate. If such an ideal situation cannot be guaranteed then there is clearly an uncertainty introduced by the changing flow conditions which may be occurring during the period of conducting the traverse(s). A service reservoir which is demand dependent is one example where flowrates can change considerably. As a minimum requirement, probe traverses should be avoided at the times of the day when the flow rate changes are most severe. Assessment of historical flow data from such an installation would provide an indication of the most suitable times in the day to perform the measurements.

- Method of Normalising – normalising involves dividing each of the measured probe velocities by a secondary or flow related signal which was recorded at the same relative time. The purpose of such an exercise is to limit the uncertainty introduced due to flow fluctuations during the course of performing the traverse. Good examples of signals with which to normalise the probe measurements include (1) a second probe positioned at a D/8 or centreline position whilst the traverse is performed with the first probe, and (2) the mean flowrate signal indicated by another flowmeter such as the meter being verified. Other signals may also be available such as pump speeds or pressure measurements. The best choice of normalising signal will depend on the design and operation of the system under consideration.

- Method of Integration – a number of different integration methods are available with which to calculate mean flowrate. One of the most popular, and the one used in ABB's *Aquaprobe* data analysis software, is the 'method-of-cubics' which has the advantage over the others that the precise radial positions are not specified by the formula. This means that as long as accurate details of the radial distances and associated velocities are recorded, this method can be used to calculate the mean velocity. After having performed a traverse, even if the precise radial distances and measured velocities are assumed to be 100% accurate, the calculated mean flowrate (no matter which method is used) will still have an associated error. The reason for this is due to the relatively small number of traversing points that are made across the traverse, typically between 7 to 13. Under all flow conditions no one method is better than the others. The uncertainty associated with the calculation of mean flowrate is therefore dependent on the method of integration employed and the precise nature of the flow.

- Uncertainty With the Use of a Probe Continuously at a Fixed Point – as described in 'Number of Traverses', a traverse may be performed in order to deduce the depth to which the probe should be inserted in order to measure the mean flow rate directly. If the insertion probe is then inserted to this depth and left continuously at this position an additional uncertainty arises if the flowrate through the pipe changes. This is because the depth required for the mean flow measurement may vary with flowrate. It is therefore recommended that if a probe is to be maintained at a fixed position while measuring varying flowrates then a comparison of flow profiles and equivalent mean positions under different flowrate conditions should be made. An additional source of uncertainty associated with maintaining a probe at a fixed point for an extended period of time is the potential for wear or blockage to the equipment.

D.3 CONCLUSIONS FROM APPENDIX D1

In order to illustrate the application of probe insertion meters in distorted flow profiles, a particularly severe asymmetric profile has been generated using a mathematically derived model. Although, this profile does not aim to replicate any installation exactly, it is considered to be similar to that which might be experienced just downstream of a gate valve which has not been completely closed. Replicated below is the diagram shown in Figure D1.1. A comparison of the D/8 measurement point velocities is provided in Table D.1 (replicated from Table D1.3) together with the mean flows as calculated using a virtual 7-point traverse of this profile.

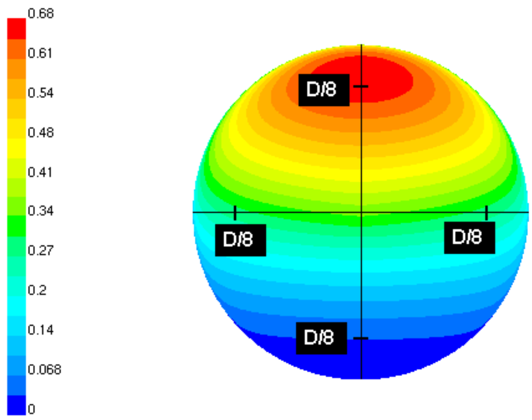


Figure D.1 Comparison of D/8 Measurement Point Velocities Used to Equate to Mean Flowrate

Table D.1 Summary of the Comparative Errors for the Profile in Figure D.1

Method	D/8 Top	D/8 Bottom	D/8 Left and Right	Vertical Traverse (7 Point)	Horizontal Traverse (7 Point)	Average of Two Traverses
% Error	+118	-88	-6	+8.4	-5.9	+1.3

In this example, where it is assumed that the D/8 position is equivalent to the mean flow rate position, it is clear that huge errors (from -88 to 118%) can result due to the installation effect. In cases where flowrates are high, and excessive vibration results when attempting a traverse, such a D/8 approximation may be unavoidable. In such cases an assessment of the affect that the installation may be having on the profile is critical. It should also be borne in mind that in such cases where a single D/8 position is assumed, and where the flow is asymmetric, there is also the potential for the profile to be affected by flowrate. This point is important when, for example, a traverse is used under low flow conditions to assess the single point insertion depth that is equivalent to the mean flow velocity. Here, the probe may be inserted to this depth and used to monitor flow over the working flowrate range of the system.

In comparison to such a D/8 approximation, the benefit to be gained by performing a full traverse is considerable. Here, despite the profile being particularly severe, in this example a single 7-point traverse results in an installation error of between –5.9 to 8.4%.

In this example where two traverses are performed, the average error reduces to just 1.3%. This figure includes the error introduced by the integration being performed with just 7 points. As will be shown in Appendix D3, this integration error is just 0.31%.

D.4 CONCLUSIONS FROM APPENDIX D2

Appendix D2 aims to quantify the errors introduced by the determination of mean flowrate using the method-of-cubics integration when a traverse is performed across what is not a true diameter. In this example, however, it is assumed that the probe is being entered square relative to the pipe axis i.e. the probe is not being tilted upstream or downstream. Figure D.2 below, as duplicated from Figure D2.1, illustrates the problem being investigated. Figure D.3, as duplicated from Figure D2.2, illustrates the virtual velocity field being analysed.

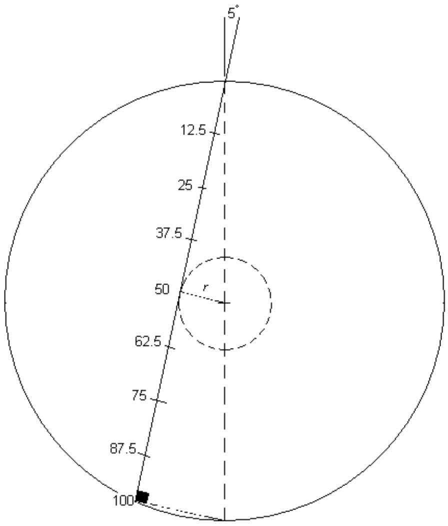


Figure D.2 Example of Probe Traversing Points Taken on a Misaligned Diam.

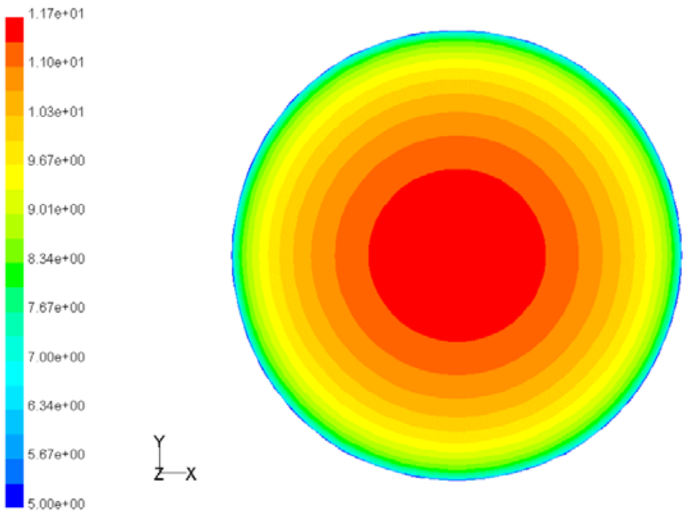


Figure D.3 Flow Velocity Distribution For Misaligned Traverse Detailed in Figure D.2

Duplicated from Table D2.2, Table D.2, is a summary of the errors introduced by the method-of-cubics formula when applied to the velocity field detailed in Figure D.3 when the misalignment of the probe is 5, 10, 15 and 20°. Although a misalignment as high as 20° has been considered here, it is estimated that 5 or 10° is likely to be the maximum order of misalignment that might be expected in practice.

Table D.2 Summary of Errors Produced Due to Misalignment of Probe

Misalignment Angle, α	Assumed Mean Velocity	Mean Velocity Corrected onto True Diameter	% Error
5°	98.14	98.30	-0.16
10°	97.67	98.29	-0.63
15°	96.93	98.27	-1.37
20°	95.93	98.26	-2.38

From Table D.2 it is clear that, as the misalignment angle increases, the error between the assumed mean velocity and the corrected mean velocity also increases. Since the probe is misaligned, the measured data does not include the maximum flowrate region at the centre point. The fact that the errors above are negative is consistent with this observation.

As detailed in Appendix D1, no units are displayed in Table D.2 for any of the mean flow velocity measurements. For any integration formula, as detailed for example in Section D2.4.3, the radial positions are non-dimensionalised, i.e. a given measurement point is expressed as the ratio of the given radial depth to the measured radius. Table D.2 is therefore applicable to any diameter of circular pipe.

Although this exercise is applicable to any diameter of pipe, the errors in Table D.2 are only directly applicable to the precise velocity field (as detailed in Figure D.3) that has been analysed. It is therefore stressed that the errors in Table D.2 should not be considered as absolute. Instead, they serve as an indication of the magnitude of the errors that should be expected when a misalignment of a probe is made through a fully developed axisymmetric profile. It is remembered that, in this example, it is assumed that the probe has been entered square relative to the pipe axis.

D.5 CONCLUSIONS FROM APPENDIX D3

Appendix D3 investigates two sources of uncertainty associated with the application of the method-of-cubics integration technique. Firstly, the errors arising from number of point velocities measured across the traverse are quantified. Secondly, the uncertainties associated with assuming a constant Von Karman coefficient of m = 7 in the integration formula are quantified.

From the assessment of the 7, 9, 11 and 13 point traverses taken across a virtual fully developed profile, the following errors associated with the use of the integration sequence have been calculated: 0.31, 0.19, 0.13 and 0.09% respectively. This means, for example, that if 7 pairs of equally spaced velocity and depth measurements are taken across a traverse, and the velocity profile is perfectly fully developed and all readings (depth and velocity) are 100% accurate, then the calculated mean flow rate using the method-of-cubics integration would still be in error by 0.31%.

Following the assessment of the uncertainty associated with the assumption of a constant m = 7 value in the method-of-cubics formula, it has been established that the magnitude of the resulting error in the mean flowrate is not insignificant. If it is assumed that the practical working range of an insertion meter in (water) flow within the Reynolds number range 1,000 to 400,000, then the equivalent range of Von Karman coefficients, m, is around 6.6 to 7.6. Table D.3 indicates the order of errors that could result at either of these extremes if no account is made for the profile effect introduced by assuming a Von Karman coefficient $m = 7.0$.

Table D.3 Summary of Percentage Errors Introduced by Assuming Given Von Karman Coefficients

No. Traversing Points	m = 6.6 % Error	m = 7.6 % Error
7	0.27%	-0.34%
9	0.21%	-0.27%
11	0.18%	-0.22%
13	0.15%	-0.19%

D.6 CONCLUSIONS

There is an ever increasing ease with which users can operate insertion probes without the need for full recognition and appreciation of the various sources of uncertainty that can contribute to the overall uncertainty of this measuring technique. This report identifies and describes these sources of uncertainty with the principle aim of providing deeper understanding so that improvements can be made to the effectiveness and accuracy of the insertion probe measuring technique.

A number of these sources of uncertainty are investigated in some detail in this report and the magnitude of the errors that can be expected have been quantified, providing further useful information to the insertion probe users. One part of this work (Appendix D1), has shown that when two perpendicular traverses are made across a severely asymmetric profile, the resulting error was just 1.3%. This compared to errors of between –5.9 and 8.4% when a single traverse was performed. The danger of performing a single point mean flow measurement at a D/8 position is highlighted by the resulting errors of between –88 and 118%.

In another investigation (Appendix D2) it was demonstrated that errors can result when an insertion probe is misaligned. For the flow profile examined it was shown that when the misalignment angle between the probe and pipe is 5, 10, 15, and 20°, errors of -0.16, -0.63, -1.37 and -2.38% are produced respectively. It was also shown that these errors are in addition to the error that is introduced due to the mis-measurement of diameter when the same tapping location is utilised.

Lastly, an investigation was performed into integration uncertainties (Appendix D3). Firstly, the errors related to the number of traversing points taken across a traverse was quantified. For the fully developed velocity profile examined it was shown that when a 7, 9, 11 or 13 point traverse is performed, errors of 0.31, 0.19, 0.13 and 0.10% were obtained respectively. This means, for example, that if 7 pairs of equally spaced velocity and depth measurements are taken across a traverse, and the velocity profile is fully developed and all readings (depth and velocity) are 100% accurate, the calculated mean flow rate using the method-of-cubics integration would still be in error by 0.31%.

Secondly, the uncertainties associated with assuming a constant Von Karman coefficient of $m = 7$ in the integration formula were quantified. The results from this analysis indicate that when m values in the range of 6.6 to 7.6 are considered, the maximum error (with a 7-point traverse) is in the order of 0.27 to -0.34%,

D.7 REFERENCES

1 NEL Report No 99/96, ‘An Investigation into the Effects of Installation on the Performance of Insertion Flowmeters’, National Engineering Laboratory, 1997.

2 NEL Flow Course, Lecture No. 7 – ‘Insertion Meters and Velocity Measuring Probes’, presented at the course ‘The Basic Principles and Practice of Flow Measurement’, National Engineering Laboratory, 2000.

APPENDIX D1 –

INSTALLATION EFFECTS – A BACKGROUND TO MEAN FLOWRATE DETERMINATION USING INSERTION PROBES AND APPLICATION TO A MATHEMATICALLY DERIVED EXAMPLE

OVERVIEW

In this Appendix, first of all, a background to probe insertion meters is discussed and a summary made of the different methods that are available to determine mean flow velocity (and therefore volumetric flowrate) using such devices. An example of a particularly severe and distorted flow is described in order to illustrate and emphasise the benefits, in terms of reduced uncertainty, of having a fully developed flow profile. This example is then described in more detail with a demonstration of how the mathematically derived asymmetric profile was produced. The model is then used to estimate the mean flow velocities that are obtained when the following probe measurements are assumed: single point measurements (D/8), a single 7-point traverse, two perpendicular 7-point traverses. The mathematically derived true mean flow velocity for the distorted profile is then computed and this is used to evaluate the errors associated with the flow velocity solutions described above (based on the probe measurements).

D1.1 PROBE TRAVERSES AND INTEGRATION TECHNIQUES

There are typically three different methods that can be employed to determine flowrate using insertion meters. Following a brief description of each of them a worked example is provided showing the errors that can result when each of the methods are applied to a particularly distorted (asymmetric) flow.

D1.1.1 D/8 Position

If the insertion meter is positioned into a fully developed (symmetric) flow at a depth equivalent to one eighth of the diameter of the pipe, the indicated flow rate approximates to the mean flowrate in the pipe. In some circumstances, for instance when the fluid velocity is severe, positioning the probe at a greater depth into the flow may cause excessive vibration of the probe (and subsequently a poor signal). In such circumstances such a D/8 approximation may well be unavoidable. If the profile is not fully developed then there is the potential for extremely inaccurate measurements.

To illustrate this, consider Figure D1.1 where the contour plot from an asymmetric velocity profile is provided. (This example is developed in more detail in Section D1.2). Such a profile may be experienced downstream of a gate valve which has not been fully closed. In the figure each shade represents the same velocity. If the D/8 positions are taken on the horizontal diameter then two similar measurements could be expected; in this example these values will be shown in Section D1.2.2 to be smaller than the actual mean velocity. If, on the other hand, positions are taken across the vertical diameter, a major discrepancy between the two readings is evident.

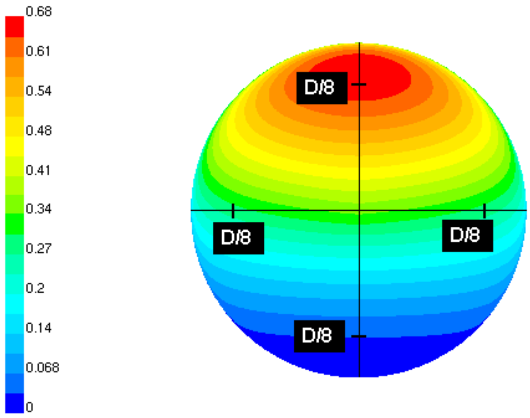


Figure D1.1 Comparison of D/8 Measurement Point Velocities Used to Equate to Mean Flowrate

D1.1.2 Centreline Position

In a fully developed flow profile the maximum flow velocity is at the centreline. If such a profile is assumed then the mean flow rate can be determined by measuring the velocity at the centre of the pipe and simply applying a correction factor. Typically, for a fully developed turbulent flow, the centreline velocity is approximately 20% higher than the mean flowrate. Therefore, if the centreline velocity is divided by the factor 1.2, the resulting figure approximates to the mean flow velocity.

From the discussion in Section D1.1.1 it is clear that the issue of inaccuracies resulting from asymmetric flow profiles will have similar implications where the centreline velocity method is used to determine mean flow velocity (and flowrate).

D1.1.3 Traverse

If a number of point velocity measurements are made across a diameter (i.e. a traverse) then this data can be assessed in order to determine the shape of the velocity profile. These local velocity measurements are then used in an *integration* to determine the mean pipe velocity and this in turn is used to ascertain the volumetric flowrate. Details relating to the *Method-of-Cubics* integration are provided in Appendix D2.

If the integration were to be performed manually, these point velocities would not simply be entered into the integration directly but averaged for nominally identical radial positions. For example, consider during a single vertical traverse, 2 measurements are made either side of the centre of the pipe at distances from the top of the pipe of D/4 and 3D/4. In terms of radial distances from the centre, both points represent a mid-way point between the centre and the pipe wall (D/4), and, in the case of an axisymmetric profile, the velocities should be identical. The average flow of these two points is determined and this entered into the integration equation for the given radial distance from the centre.

Where the flow profile is distorted the velocities at these two nominally identical positions may not be the same. However, since the average value of the two velocities used in the integration, this ensures that account is being made for the distorted nature of the flow.

Multiple Traverses

Consider, for example, during a single vertical traverse, that two point velocities are made at two nominally identical positions of D/4 either side of the centre. If a horizontal traverse were also to be performed, and again included the D/4 and 3D/4 points (measured from the top of the pipe), then the average velocity at the radial distance of "D/4" from the centre is given by the average of all the four measurements. This process of averaging an asymmetric flow into an equivalent axisymmetric flow has the result of reducing the error in the integrated flowrate solution. In practice, the instrumentation associated with the measurement probe may well perform the analysis completely 'behind the scenes' and simply display the mean flow as calculated for the traverse being considered. The mean flow results from averaging a horizontal and a vertical traverse, calculated in this manner is equivalent to performing the integration on a data set where first all the equivalent radial distance velocities from both traverses are averaged. This is discussed in more detail in Section D1.2.4.

D1.2 WORKED EXAMPLE

The artificial asymmetric velocity profile described in Section D1.1.1 has been generated using the following formula:

$$u = \left(\frac{R - r\cos\alpha}{2R}\right)^{c}\left(\frac{R-r}{R}\right)^{1/7} \quad \text{.................................... Equation D1.1}$$

where u is the relative velocity at any point in the cross section defined by r (the radial distance from the centre), R (radius) and α (the angle subtended from a line drawn vertically downwards from the centre and rotated clockwise). This value of u is dimensionless. Figure D1.2 illustrates the variables in Equation D1.1.

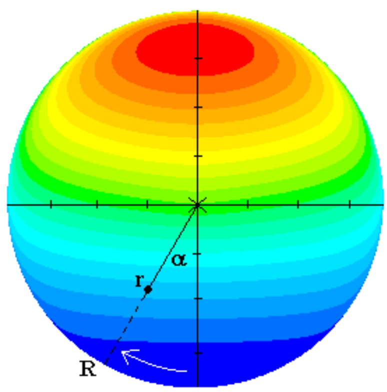


Figure D1.2 Comparison of D/8 Measurement Points Used to Equate to Mean Flow Rate

The extent of asymmetry, shape (or flatness) of an axisymmetric profile, is defined by the value of the Von Karman coefficient, *'c'*. As is discussed in Section D2.4.2, the '1/7' term in Equation D1.1, is equivalent to the '1/*m*' term in Equation D2.2. Here, this coefficient, *c*, is dependent on Reynolds number, but as discussed in Section D2.4.2, a value of around 7 is considered appropriate.

In this example, a pipe diameter of 203 mm has been assumed and when c = 1.5, Equation D1.1 reduces to 0.3536 at the centre (when r = 0). It can be shown that if Equation D1.1 is integrated with respect to r and α over the entire cross-section, for the given pipe diameter and c value, the mean flow velocity (to four decimal places) is exactly 0.3081.

Tables D1.1 and D1.2 summarise the data obtained from a vertical and horizontal 7-point traverse calculated using Equation D1.1. In the following sections, using the data presented in these tables, the mean flows are calculated on the basis of: D/8, single traverses (both horizontal and vertical) and the average of two perpendicular traverses. The resulting errors are quantified and these are summarised in Table D1.3.

Table D1.1 7 Point Vertical Traverse Using Equation D1.1 (Equally Spaced)

Order Measured	Vertical Insertion Depth (mm)	Velocity	*i*	Radial Distance from Centre (mm)	Average Velocity
1[1]	25.375 (α = 180°)	0.671	3	76.125	0.354
2	50.750 (α = 180°)	0.588	2	50.750	0.351
3	76.125 (α = 180°)	0.474	1	25.375	0.347
4	101.5 (α = 0 or 180°)	0.354	0	0.000	0.354
5	126.875 (α = 0°)	0.220	1	25.375	-
6	152.25 (α = 0°)	0.113	2	50.750	-
7[1]	177.625 (α = 0°)	0.036	3	76.125	-

[1]D/8 Position

Table D1.2 7 Point Horizontal Traverse Using Equation D1.2 (Equally Spaced)

Order Measured	Vertical Insertion Depth (mm)	Velocity	*i*	Radial Distance from Centre (mm)	Average Velocity
1[1]	25.375 (α = 90°)	0.290	3	76.125	0.290
2	50.750 (α = 90°)	0.320	2	50.750	0.320
3	76.125 (α = 90°)	0.339	1	25.375	0.339
4	101.5 (α = 90° or 270°)	0.354	0	0.000	0.354
5	126.875 (α = 270°)	0.339	1	25.375	-
6	152.25 (α = 270°)	0.320	2	50.750	-
7[1]	177.625 (α = 270°)	0.290	3	76.125	-

[1]D/8 Position

D1.2.1 Mean Flow Solutions of these Vertical and Horizontal Traverses Using the Method-of-Cubics Integration

Tables D1.1 and D1.2 have been presented in the way they have in order to illustrate the data preparation that is first required before performing the method-of-cubics integration by hand. This integration technique is discussed in detail in Appendix D2.

It is appreciated that instruments like ABB's aquaprobe may well perform all the computation without intervention of the user but this detail was considered as a useful addition for those readers who might want a deeper understanding of the basis of integration techniques.

When the data in the last two columns in Table D1.1 is applied in the method-of-cubics integration, the calculated mean flow velocity for the vertical traverse is 0.334. Similarly, when the data in the last two columns in Table D1.2 is applied, the calculated mean flow velocity for the horizontal traverse is 0.290.

D1.2.2 Comparison of D/8 Velocities

The following summarises the velocity point values at the D/8 positions (Figure D1.1 and Tables D1.1 and D1.2) obtained from Equation D1.1 when α = 0, 90, 180 and 270° respectively: 0.036, 0.290, 0.671 and 0.290. From the data it is clear that there is a huge difference in the estimated mean flowrates between the two 'equivalent' points on the vertical: 0.036 and 0.671 (α = 0 and 180° respectively). The low velocity of 0.036 is some 88% less than the actual mean flow rate of 0.308. Similarly the high velocity of 0.671 is 118% higher than the mean velocity. It is also noted that the horizontal points at 90 and 270° have the same value, and, on this occasion (due to the value of c = 1.5), they are around 6% less than the actual mean flow rate of 0.308.

D1.2.3 Comparison of Centreline Velocities and Profile Factors

Section D1.1.2 stated that, for a fully developed profile, the centreline velocity is larger than the mean flow rate. The Velocity Profile Factor can be defined as the ratio of the mean velocity to the (maximum) velocity at the centre point. For the data generated across the vertical traverse, the flow velocity at the centre is 0.354 but as discussed above this is not the maximum due to the flow being disturbed. If a horizontal traverse were performed in isolation, the maximum flow measured would indeed be a maximum of 0.354 at the centre. It might therefore be wrongly assumed that the velocity profile was fully developed. On this basis, and for a fully developed flow profile with a Von Karman coefficient = 7, the mean flow integration solution for the data in Table D1.2 is 0.290. This results in a profile factor = 0.82 (= 0.290/0.354). This assumed profile factor can now be compared with the exact profile factor since the actual mean flowrate is known to be 0.3081; giving a profile factor of 0.87 (= 0.308/0.354). This represents an error of -6%.

D1.2.4 Comparison of Various Traverse Integrations

The traverse flow data in Section D1.2.1 Tables D1.1 and D1.2 may be integrated to calculate mean flow rates. Integrating the vertical traverse data in Table D1.1, gave a mean flow rate of 0.334. Compared with the true mean velocity of 0.308, this represents an error of +8.4%.

Similarly, the integrated mean flow velocity of the horizontal traverse is 0.290, and represents an error of -5.9%. (This is the same value of the error described in Section D1.2.3 when assessment was made in terms of Profile Factors). Although these integrated mean velocities will incorporate errors due to the integration technique itself, this exercise demonstrates the magnitude of the errors that could be imposed from simply taking a single traverse across a badly distorted profile.

Section D1.1.3 discussed the process of averaging the velocity measurements for nominally identical radial positions. Since two traverses have been performed this gives 4 velocity measurements at each nominally identical radius. Averaging these velocities at each radial distance and performing the integration, results in an average mean velocity of 0.312. Comparing this value with the true mean velocity of 0.308, gives an error of just +1.3%, demonstrating the benefit of taking two traverses instead of just one.

The average flow velocity of 0.312 just described was calculated by integrating the averaged velocities from each of the four nominally identical radial positions. It is noted that this figure is equivalent to the average of the two mean velocities calculated from the vertical and horizontal traverses; 0.334 and 0.290 respectively.

Provided in Table D1.3 is a summary of the errors from the analysis of the distorted flow profile described in Appendix D1.

Table D1.3 Summary of the Comparative Errors for the Profile Detailed in Figure D1.1 (and Figure D1.2)

Method	D/8 Top	D/8 Bottom	D/8 Left and Right	Vertical Traverse (7 Point)	Horizontal Traverse (7 Point)	Average of Two Traverses
% Error	+118	-88	-6	+8.4	-5.9	+1.3

APPENDIX D2 –

MISALIGNMENT OF PROBE TRAVERSE

D2.1 INTRODUCTION

When a welded boss on the outside of the pipe is set not exactly square to the pipe there arise two main sources of uncertainty associated with the application of a probe traverse. The first relates to the mis-measurement of the pipe bore diameter which has a direct bearing on the measurement of volumetric flowrate. The second is the error introduced in the integration formula resulting from the traverse not being entered across a true diameter.

D2.2 UNCERTAINTY WITH DIAMETER MEASUREMENT

Consider a tapping point which has been installed on a piece of pipework in order to allow the application of a probe traversing technique. A number of sources of uncertainty are associated with how well this tapping point is installed. The first example of uncertainty is when the tapping point is also used to measure the pipe diameter, with an appropriate measuring gauge; the diameter measurement is fundamental to the calculation of volumetric flowrate. If the tapping boss is not perfectly square to the pipe laterally, then an incorrect diameter will be measured. In such a case, and assuming a perfectly circular cross section, the measured diameter will actually be less than the true diameter. Also, when the tapping point is not square to the axial plane of the pipe, the diameter will be over-estimated. The errors introduced due to diameter mis-measurement are detailed in Appendix F; a study into the uncertainty of clamp-on ultrasonics.

D2.3 UNCERTAINTY WITH APPLICATION OF THE FLOW INTEGRATION FORMULA

There are two issues relating to the uncertainty in integrating the flow using an integration formula.

D2.3.1 Inherent Inaccuracy of the Flow Integration Formula

This uncertainty relates to how well the integration formula would calculate the mean flowrate if it could be assumed that there are no errors associated with any of the traverse measurements (radial position and velocity at each position). This topic is investigated fully in Appendix D3.

D2.3.2 Misalignment of Probe Traverse

The second, and slightly less obvious source of uncertainty, is in the application of the integration formula when the probe traverse is conducted on a traverse plane that is not on the true diameter because of misalignment of the tapping. Here, whether the integration formula is ‘Log-linear’, ‘Log-Tchebycheff’ or the ‘Method-of-Cubics’ [Flow Course Notes, 2000], they all assume that the measured points across the traverse lie on an actual diameter.

In the following worked example, Figure D2.1, on a nominal 100 mm diameter pipe, a seven point probe traverse is conducted with an angular misalignment of the probe

(α), = 5°. Following the methodology developed in this example the technique is applied to angular misalignments of 10, 15 and 20°. The resulting errors from these traverses are summarised in Table D2.2.

D2.4 WORKED EXAMPLE

D2.4.1 The Scenario

Imagine that the technician performing the traverse was interested to examine if the flow profile was distorted. Here, flow velocities at nominally identical positions either side, and including, the assumed centre line position would be made. Summarised in Table D2.1 are the velocity measurements that are assumed to have been made at three radial positions either side of the assumed centre line, making a total of 7 pairs of measurements. The order the measurements were made, as indicated in Table D2.1, were from one side, through the (assumed) centre point, to the other side. A diameter measurement has also been made with a suitable bore gauge and the internal diameter (incorrectly) measured to be exactly 100.0 mm.

D2.4.2 Assumed Velocity Profile

In order to work through an example such as this, in a similar way to that detailed in Section D1.2, velocity profiles derived using a mathematical formula have been used. Although this is not 'real' data, the advantages of this approach are that the profiles produced are close to those experienced in practice. Secondly, there is only a minimal uncertainty associated with the numbers produced, the only source of uncertainty in the calculations being due to rounding errors. It is for this reason that throughout the analysis, the data has been presented with what may appear to be more significant figures than might have been thought necessary. The assumed profiles in the following analysis have been produced in accordance with Equation D2.2. Here, the centre line velocity, V_0 was 120, the *m* coefficient [Flow Course Notes, 2000] is 7.0, the insertion depths were as measured and the true radius is as calculated in the next section. Figure D2.2 details the velocity field being investigated.

D2.4.3 Flow Integration Calculation using 'Method-of-Cubics'

In this example the 'method-of-cubics' formula will be used to derive the mean pipe velocity, V_{mean}. The 'method-of-cubics' formula [Flow Course Notes, 2000] is:

$$\begin{aligned}
V_{mean} = {} & V_0\left[\frac{5}{12}\bar{r}_1^{\,2} - \frac{1}{12}\bar{r}_2^{\,2} + \frac{1}{12}\frac{\bar{r}_1^{\,3}}{\bar{r}_2}\right] + V_1\left[\frac{1}{6}\bar{r}_1^{\,2} + \frac{2}{3}\bar{r}_2^{\,2} - \frac{1}{12}\bar{r}_3^{\,2}\right] \\
& - V_2\left[\frac{1}{12}\frac{\bar{r}_1^{\,3}}{\bar{r}_2}\right] + \sum_{i=2}^{i=n-2} V_i\left[-\frac{1}{12}\bar{r}_{i+2}^{\,2} + \frac{2}{3}\bar{r}_{i+1}^{\,2} - \frac{2}{3}\bar{r}_{i-1}^{\,2} + \frac{1}{12}\bar{r}_{i-2}^{\,2}\right] \qquad \text{……… Equation D2.1} \\
& + V_{n-1}\left[\frac{1}{2}\bar{r}_n^{\,2} + \frac{1}{12}\bar{r}_{n-1}^{\,2} - \frac{2}{3}\bar{r}_{n-2}^{\,2} + \frac{1}{12}\bar{r}_{n-3}^{\,2}\right] \\
& + V_n\left[\frac{m}{m+1}\left(1-\bar{r}_n^{\,2}\right) + \frac{1}{12}\frac{\left(\bar{r}_n^{\,2} - \bar{r}_{n-1}^{\,2}\right)^2}{m\left(1-\bar{r}_n^{\,2}\right)} + \frac{7}{12}\bar{r}_n^{\,2} - \frac{2}{3}\bar{r}_{n-1}^{\,2} + \frac{1}{12}\bar{r}_{n-2}^{\,2}\right]
\end{aligned}$$

where V_0, V_1, V_2,.. V_n, are the velocities measured at the centre-line and then the 1st, 2nd, … nth radial positions from the centre, $\bar{r}_i$ is the dimensionless ratio r_i/R of the i th measuring position from the centre-line at a radius *r*, where *R* is the internal radius of the pipe, and *m* is the exponent of the Von Karman formula for the velocity distribution close to the conduit wall where

$$\frac{V_i}{V_0} = \left(1 - \frac{r_i}{R}\right)^{\frac{1}{m}} \qquad \text{……………………………..…….. Equation D2.2}$$

D2.4.4 Solution – Assuming (Incorrectly) that the Acquired Data was on the Diameter

Using the 7 point probe traverse data in Table D2.1 (4^{th} and 6^{th} columns), the 'method-of-cubics' formula (detailed above) was used to calculate the mean pipe velocity. A spreadsheet was used to perform this calculation and resulted in a mean flow velocity of V_{mean} = 98.1399. This is the calculated solution where no account is made by the technician performing the probe traverse for any misalignment of the probe. Here, it is incorrectly assumed that the probe is being entered square to the pipe and the measurements are being made on the true diameter.

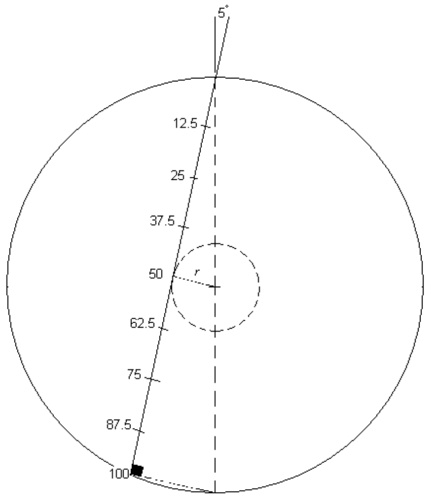


Figure D2.1 Example of Probe Traversing Points Taken on a Misaligned Diameter

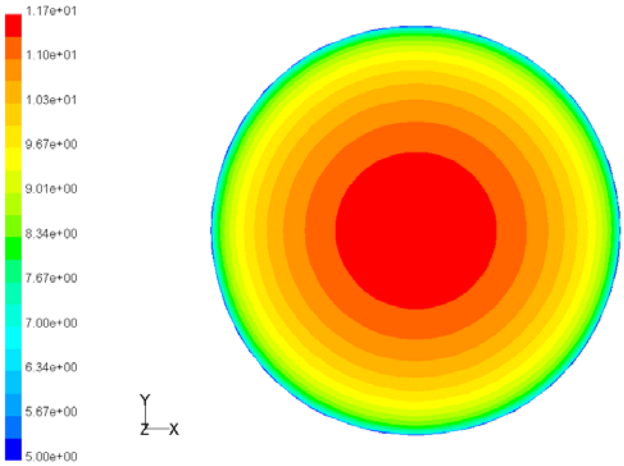


Figure D2.2 Flow Velocity Distribution For Misaligned Traverse Detailed in Figure D2.1

D2.4.5 Data Correction – Description of the Problem

Due to the misalignment of the probe, the traverse velocities do not lie on an actual diameter. Consider the measured velocity at the assumed centre point. Since the maximum velocity for a fully developed profile lies at the centre, this means that the measured velocity at the assumed centre point will be less than the actual unmeasured velocity at the actual centre point. The implications of this are that either: (1) the measured velocities across the traverse require to be corrected in order to reflect the actual radial positions that were measured, or, (2) the measured velocities across the traverse require to be correlated to the corrected radial positions from the actual centre point rather than the incorrectly assumed centre point.

In the following analysis, the second of these two methods has been chosen.

D2.4.6 Correction of Radial Distances onto a Diameter

Consider the 4th measured point in Table D2.1. This point, at 50 mm from the top of the inside of the pipe, was intended to represent the central point since the diameter was (incorrectly) measured to be 100 mm. From Figure D2.1 it is clear that the velocity measured at this point, if a fully developed profile is assumed, corresponds to the radial velocity contour at a distance, *r*, from the true centre point.

First of all, the correct diameter is required. This is calculated using Cos α = Measured Diameter (= 100 mm) / D_{true}, where D_{true} = true diameter. This gives D_{true} = 100.382 mm and r_{true} = 50.191 mm, where r_{true} = true radius.

For any radial position, with an insertion depth, *a*, and distance, *r*, from the true central point, simple trigonometry gives $r^2 = a^2 + r_{true}{}^2 - 2ar_{true}Cos\alpha$. For example, the 4th probe measuring point at an insertion depth of 50 mm is calculated to be 4.37 mm away from the true centre. Therefore, the velocity associated with this 4th point, instead of being at the centre point, corresponds to the radial velocity contour at a distance *r* = 4.37 mm from the true centre.
By applying this methodology to each of the measured points in Table D2.1 the corrected radial distances from the true centre are calculated – these are also summarised in Table D2.1.

Table D2.1 Summary of Probe Traverse Data – Misaligned by 5^o

Order Measured	Insertion Depth (mm)	Velocity	Average Velocity	*i*	Radial Distance from Assumed Centre (mm)	Radial Distance to Each Point from Actual Centre Point (mm)
1	12.5	98.315	98.315	3	37.5	37.754
2	25	108.510	108.510	2	25	25.380
3	37.5	114.862	114.862	1	12.5	13.243
4	50	118.447	118.447	0	0	4.374
5	62.5	114.862	-	1	-	-
6	75	108.510	-	2	-	-
7	87.5	98.315	-	3	-	-

D2.4.7 Estimation of the True Velocity at the Centre

The ‘method-of-cubics’ integration requires the value of the measured velocity at the centre of the pipe. Since the probe was misaligned, as described above, the velocity measured at the assumed central position has to be less than the actual velocity at the centre. Since no probe measurement was actually made at the true centre point, the flow is calculated using the following formula [Flow Course Notes, 2000], where *i*, is the i^{th} measuring position from the actual centre point:

$$V_0 = \frac{V_i}{[1-(\frac{r_i}{R_i})]^{\frac{1}{m}}} \Rightarrow \frac{V_1}{[1-(\frac{r_1}{R_1})]^{\frac{1}{m}}} \quad \text{when } i = 1 \qquad \text{……... Equation D2.3}$$

From Table D2.1, the previous (incorrect) centre point velocity V_0 = 118.447. Since the velocity at this point has been shown to be equivalent to a velocity measured on a radial position at a distance 4.37 mm from the true centre point, this information can be used in Equation D2.3 to calculate the actual velocity at the true centre point. Here, the old V_0 becomes V_1 = 118.447, r_1 = 4.37 mm and R_1 = true radius = 50.191 mm. This results in a new V_0 = 120. As described in Section D2.4.2, this was the maximum velocity assumed when generating the data required to represent the velocity profile data in the first place.

D2.4.8 Flow Integration Calculation With Corrected Radial Position Information

In order to calculate the error associated with the misalignment, the integration is repeated but this time with the ‘measured’ velocity data corresponding to the corrected radial positions on the true diameter. When performing the integration this time, although an additional velocity/position data point has been established for the actual centre point, the integration will still be performed using the data corresponding to a 7-point traverse. The reason for this is in order not to introduce errors associated with the number of traversing points used in the integration (see Appendix D3). The point corresponding to the reading at 4.37 mm away from the true centre point will be ignored and the true velocity = 120 at the true centre point (r = 0) will be used.

The corrected radial positions can now be correlated with the measured velocities and the method-of-cubics integration performed in order to calculate the required mean flow velocity resulting in a mean flow velocity of 98.3009.

D2.5 CONCLUSIONS

In this example it has been shown, that for the assumed velocity profile and with a misaligned 7-point traverse (misaligned by 5°), the mean velocity is calculated to be 98.1399. This compares to the mean velocity that would have been calculated, had the probe been inserted square to the pipe, of 98.3009. The error therefore associated with the misalignment of the probe by 5°, is [(98.1399-98.3009)/98.3009] x 100% = -0.16%.

Furthermore, it should also be remembered that there are errors associated with the integration technique itself (see Appendix D3). However, the comparative velocities calculated here both have this error and so can be considered to have balanced each other out.

D2.5.1 Application of Methodology to Further Misalignment of the Probe

Repeating the above exercise, the methodology described above has been applied for probe misalignment angles of 10, 15 and 20° and a summary of the errors introduced is provided in Table D2.2.

Although this exercise is applicable to any diameter of pipe, the errors in Table D2.2 are only directly applicable to the precise velocity field (as detailed in Figure D2.2) that has been analysed. It is stressed therefore that the errors in Table D2.2 should not be considered as absolute. Instead, they serve only as an indication of the magnitude of the errors that should be expected when a misaligned probe is traversed through a fully developed axisymmetric profile.

Table D2.2 Summary of Errors Produced Due to Misalignment of Probe

Misalignment Angle, α	Assumed Mean Velocity	Mean Velocity Corrected onto True Diameter	% Error
5°	98.1399	98.3009	-0.16
10°	97.6739	98.2885	-0.63
15°	96.9304	98.2747	-1.37
20°	95.9285	98.2642	-2.38

D2.6 FURTHER WORK

The technique developed here could be applied to other misalignment angles, different number of traversing points and different flow profiles in order to generate a fuller understanding of how probe misalignment affects the errors associated with the application of the integration formula.

APPENDIX D3 –

INTEGRATION UNCERTAINTIES

D3.1 INTRODUCTION

A number of factors influence the uncertainty associated with the integration method employed. These include: (1) the number of point velocities measured across the traverse, (2) the integration technique itself and (3) the requirement of one of the commonly used integration sequences to assume a particular velocity profile (Von Karman coefficient).

D3.1.1 The Scenario

In the following discourse, an 'ideal' fully developed velocity profile with maximum flow velocity at the centreline, V_0, and Von Karman coefficient, m, is assessed in order to quantify the uncertainties associated with points (1) and (3) described above. The details of the analysis described here provide sufficient detail to allow a similar application of the methodology to different integration techniques (point (2)). For the purposes of this project, only the method-of-cubics integration technique has been assessed.

The assumed profile is derived from Equation D3.1, where the velocity V_i, at the i th measuring point is given by:

$$V_i = V_0 \times [1 - (\frac{r_i}{R_i})]^{\frac{1}{m}}$$ …………………………………..……… Equation D3.1

and where r_i is the radial distance to each point and R is the Radius of the pipe bore.

For the flow profile defined by Equation D3.1, it can shown, that the mean flow velocity, V_{mean}, is given exactly by:

$$V_{mean} = V_{\max}\left[\frac{2m^2}{(m+1)(2m+1)}\right]$$ …………………………………..……. Equation D3.2

Since the exact solution can be calculated this allows a quantifiable assessment to be made of the sources of uncertainties detailed above.

D3.1.2 Method-of-Cubics Integration

In order to be as true to real life as possible, the integration analysis is conducted here using the 'method-of-cubics' integration technique – this is the same one as is used by ABB in their *Aquaprobe* insertion meter software.

D3.1.3 Computer Program

The method-of-cubics formula, Equation D2.1, was incorporated into a Microsoft EXCEL Visual Basic program. This allows the user to easily enter any number of radial position/velocity points across the chosen diameter and the program will automatically calculate the integrated mean flow velocity.

In the exercise described here, the velocity data was derived from the fully developed profile defined by Equation D3.1. This allows the integrated solution using the program to be compared with the exact solution defined by Equation D3.2.

Assessment of Program

Before performing the analysis, and due to the complexity of the method-of-cubics formula, it was wise to first validate the EXCEL program. This was achieved by generating the velocity profiles (as defined by Equation D3.1) over an increasingly large number of radial positions and comparing the integrated mean flow rates with the known exact solution. The results from this analysis showed that as the number of radial positions was increased, the error reduced. When the number of radial positions is around 100, the associated error in the integration can be shown to be around just 0.001%. In practice, of course, such a large number of points is infeasible. This exercise does, however, demonstrate that the code is operating correctly.

D3.2 NUMBER OF TRAVERSING POINTS

As described, the method-of-cubics integration can be shown to be extremely accurate if a very large number of traversing points are obtained. Since this is impractical it is of interest to examine the errors associated with taking far fewer points.

It is quoted in a report produced by the water company that 7, 9, 11 and 13 traversing points are performed for diameters of 100 to 400 mm; 401 to 500; 501 to 600 and >600 mm respectively. On the basis of these numbers of traversing points, the following errors associated with the use of the integration sequence have been calculated: 0.313, 0.189, 0.126 and 0.09% respectively. For example, reference to Table D3.2 gives a velocity of 98.31 for a 7-point traverse for an assumed m = 7.0, whereas the exact mean velocity solution is 98.00. This gives an error of 0.31% (= (98.31-98.00)/98.00).

In summary therefore, if 7 pairs of equally spaced velocity and depth measurements are taken across a traverse, and the velocity profile is perfectly fully developed and all readings are 100% accurate, the calculated mean velocity using the method-of-cubics integration would still be in error by the order of 0.31%.

D3.4 INTEGRATION TECHNIQUE

Efforts have been concentrated here on assessing the method-of-cubics integration since this is the method applied by ABB in their *Aquaprobe*.

Two other methods available are the ‘Log-linear’ and ‘Log-Tchebycheff’ methods. Both make use of the theoretical velocity distribution that occurs in fully developed pipe flow. Here, radial positions are defined where velocity measurements are required to be taken. The mean pipe flow is then derived simply by calculating the arithmetic mean of these velocities. An obvious drawback with such techniques are that the velocities at precisely defined radial positions are required. Errors will therefore be introduced where a probe is assumed to be on the required radial position when in fact it is not. The method-of-cubics integration on the other hand is much more forgiving since measurements can be made at any points across the diameter. This of course assumes that the actual radial positions are recorded and used in the integration. This option is not available with the Log-linear and Log-Tchebycheff methods.

The Log-linear and Log-Tchebycheff methods both make use of theoretical velocity distributions, as has been the approach adopted here. It would therefore be possible to apply a similar methodology to these integration techniques.

D3.5 VELOCITY PROFILE EFFECT (VON KARMAN COEFFICIENT)

A term used in the method-of-cubics formula is the Von Karman coefficient, *m,* (see Section D2.4.3). This term, which appears in the theoretical velocity profile defined by Equation D3.1, essentially dictates the flatness of a symmetrical velocity profile and is dependent slightly on the Reynolds number. For hydraulically smooth pipes, *m* varies between 6.6 to 10 for Reynolds numbers between 2.3E4 and 2.0E6 Cubics' [Flow Course Notes, 2000]. These data have been plotted in Figure D3.1 and a quadratic trendline is used to define a relationship between *m* and Reynolds number.

Table D3.1 – Approximate Values of '*m*' in Hydraulically Smooth Pipes

Reynolds Number	2.3×10^4	1.1×10^5	1.1×10^6	2.0×10^6
'm'	6.6	7.0	8.8	10

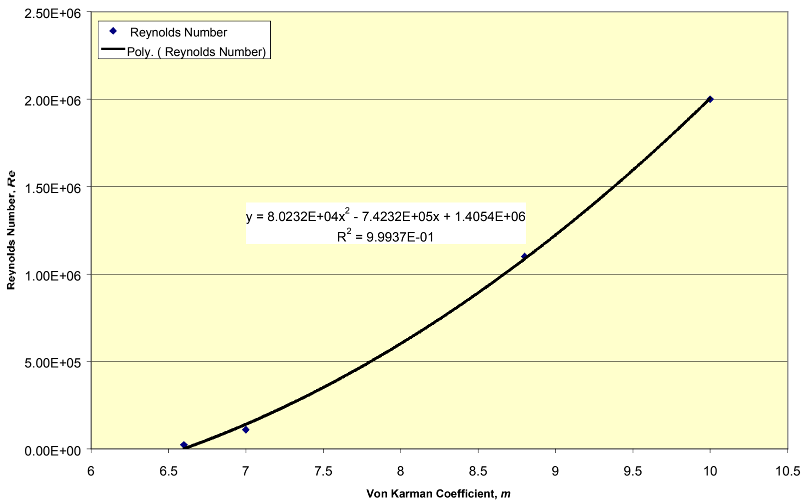


Figure D3.1 - Reynolds Number Versus Von Karman Coefficient

Since *m* is shown to depend on Reynolds number, and therefore flowrate, this means that this parameter should not simply be assumed to be a constant in the method-of-cubics integration. There is a growing tendency for probe manufacturers to supply all the necessary data acquisition and analysis software as part of the one package of equipment. It is unclear, however, whether account is made of the variations in *m* that can be expected over the range of different flowrates to which a probe can be subjected. In a private discussion with a prominent industrialist from one of the main flowmeter manufacturers it was suggested that *m* was most likely assumed to be constant.

In order to investigate if the ABB *Aquaprobe* assumes a constant value for *m* or whether it is a function of the flowrate (Reynolds number), a number of flow profiles obtained by the water company have been re-integrated using both ABB's own software – 'Aquaprobe Flow Profiling Utility', Version 2.0 and the EXCEL integration program described in Section D3.1.3.

D3.5.1 The Procedure – Changing '*m*' so that the Mean Velocities Equate

The procedure adopted was to reanalyse the flow profile data on each certificate using the ABB software. The results from each analysis were exactly the same as before and gave assurance that this software was calculating the same figures as previously reported on the certificates.

The next stage was to perform the integration on each profile using the EXCEL code. Here, the insertion depths and true velocities as detailed on the certificates were used in the analyses – the aim being to reproduce the mean velocities as detailed on the certificates. Since, as described in Section D3.5, the method-of-cubics integration requires a value to be assumed for the *m* coefficient, this parameter was changed in order that the integrated mean velocity using the EXCEL program equated with the value on the certificate.

D3.5.2 Results – Estimation of Errors

In every case investigated, the mean flow velocity using EXCEL was reproduced when '*m*' was taken to be 7.0. Although the Reynolds numbers associated with these cases were all within a fairly tight band (28,200 to 37,800) it is felt that the Aquaprobe software is likely to use a constant value of '*m*'.

On the assumption that an insertion meter may be suitable over a range of Reynolds numbers between 2.3×10^4 to 3.0×10^6, Figure D3.1 indicates that '*m*' varies in the range from 6.61 to 11.05. The following analysis was performed in order to quantify the errors associated with assuming such a constant value for '*m*' (=7):

Using the EXCEL program, a pipe diameter of 100 mm and a maximum flow velocity at the centreline, V_0 = 120, were assumed. For each chosen number of traversing points, 7, 9, 11 or 13, the calculated mean velocity, $V_{m=7}$, was then established. As discussed in Section D3.2, there is an error associated with this solution but for the purposes of this exercise, comparisons are made with this inexact solution in order not to account for a second time the uncertainty associated with the number of traversing points. Table D3.2 lists the calculated mean flow velocities for each of the given number of traversing points when *m* = 7.0.

The procedure now was to change the value of *m* to one of m = 6.6, 8, 9, 10 or 11, and for each of the number of traversing points detailed in Table D3.2 establish the value of V_0 required for the mean velocity solution to be the same as before. This procedure allows the velocity profile to be established, for which the mean velocity is the same. This new profile is then integrated, with *m* = 7, again using the method-of-cubics, in order to calculate the solution for this inappropriately assumed *m* value. The resulting errors arising from the use of the wrong *m* value could then be established and these are summarised in Table D3.3 To check the methodology described above, an imaginary profile with 101 points across the traverse was also applied, the resulting errors for this case are also detailed in the table.

Table D3.2 Mean Velocity Solutions (Method-of-Cubics) for Given Number of Traversing Points (R=50, V_0 = 120, m = 7.0)

Number of Traversing Points	Mean Velocity Solution (using Method-of-Cubics)
7	98.3066
9	98.1853
11	98.1239
13	98.0887
101	98.0018

Table D3.3 Velocity Data and Associated Errors Assuming Various Velocity Profiles and Number of Points Across the Traverse

V_0 = 120 ∅ = 100		Mean Velocity Assuming Velocity Profile Defined By:					
No. Trav. Points	**$V_{m=7}$ (Exact = 98.00)**	***m* = 6.6**	***m* = 7**	***m* = 8**	***m* = 9**	***m* = 10**	***m* = 11**
7	98.307	98.574	98.307	97.741	97.287	96.914	96.604
		(V_0 = 121.380)	(120)	(117.177)	(115.004)	(113.279)	(111.877)
error (%)		0.27%	0	-0.58%	-1.04%	-1.42%	-1.73%
9	98.185	98.396	98.185	97.737	97.375	97.077	96.827
		(V_0 = 121.388)	(120)	(117.162)	(114.976)	(113.242)	(111.832)
error (%)		0.21%	0	-0.46%	-0.82%	-1.13%	-1.38%
11	98.124	98.296	98.124	97.755	97.455	97.207	96.999
		(V_0 = 121.391)	(120)	(117.154)	(114.963)	(113.224)	(111.810)
error (%)		0.18%	0	-0.38%	-0.68%	-0.93%	-1.15%
13	98.089	98.234	98.089	97.776	97.521	97.309	97.130
		(V_0 = 121.393)	(120)	(117.150)	(114.956)	(113.214)	(111.798)
error (%)		0.15%	0	-0.32%	-0.58%	-0.79%	-0.98%
101	98.002	98.017	98.002	-	-	-	97.888
		(V_0 = 121.398)	(120)				(111.769)
error (%)		0.02%	0	-	-	-	-0.12%

D3.6 CONCLUSIONS

From perusal of Table D3.3 it is clear that for any given value of *m,* the error reduces as the number of traversing points increase. This is as expected since a greater number of points means that the profile changes across the diameter, which are most severe close to wall, are being detailed more accurately. As the value of *m* departs more and more from a value of 7.0, for any given number of traversing points, the error is seen to increase. This is again as expected since the profile shape is changing more and more.

In reality, it is considered that the range of Reynolds number with which a probe is likely to be subjected is probably not nearly as great as the 2.3 x 10^4 to 3 x 10^6 range described in Section D3.5. One reason for this view is the excessive vibration that can be observed in moderately sized mains when the mean velocity is too high.

If a mean flow velocity of around 0.1 to 2 m/s is considered appropriate then the range of Reynolds numbers associated with pipe diameters of 100 mm to 2 m is around 1,000 to 400,000. From Figure D3.1, (although the quadratic has been extrapolated slightly at the lower end), corresponding '*m*' values are around 6.6 to 7.6. On this basis, and with reference to Table D3.3, the maximum error (by interpolation of the 7-point traverse errors at *m* = 6.6 and *m* = 8) is in the order of 0.27 to -0.34% respectively. Table D3.4 details a summary of the percentage errors introduced by assuming Von Karman coefficients of 6.6 and 7.6.

Table D3.4 Summary of Percentage Errors Introduced by Assuming Given Von Karman Coefficients

No. Traversing Points	m = 6.6 % Error	m = 7.6 % Error
7	0.27%	-0.34%
9	0.21%	-0.27%
11	0.18%	-0.22%
13	0.15%	-0.19%

APPENDIX E

CASE STUDY REPORT:
AN INVESTIGATION INTO THE PROBE PROFILING TECHNIQUE AT A SPECIFIC INSTALLATION

EXECUTIVE SUMMARY – APPENDIX E

The experience of this particular water company with the application of insertion probes for the verification of permanently installed full bore meters, typically electromagnetic flow meters, is very good. Overall they believe that the probe traversing technique provides a reliable and repeatable method of verifying the performance of flowmetering devices.

However, in one particular design of installation, where an electromagnetic meter is located in a reduced diameter bypass, the water company have found meter verifications (using insertion probes downstream of the bypass) to be failing to meet expectations. Here, comparisons between the mean flowrate indicated by the insertion probe and that indicated by the electromagnetic meter show discrepancies in the order of 8, 12 and even as high as 20%. It was therefore decided to investigate the installation and this report presents the findings from this work. It is emphasised that this installation has been chosen for investigation because the experience of this water company with this particular installation is relatively poor.

In order to investigate and quantify how the installation was affecting the velocity profile, the installation was modelled using computational techniques. A virtual probe traverse was then performed at either side of the installation using the computer-generated data and the mean flowrates calculated; the difference between these figures is assumed to be due to the installation effect. The resulting error for a 7-point traverse was only around 3% and was somewhere short of the 8, 12 or even 20% that the water company have experienced. The computer model was then adapted in order to introduce a further disturbance to the flow through the inclusion of a partially closed gate valve. The resulting change to the velocity profile at the tapping point was negligible and another explanation was required to be found to account for the difference between the modelled and measured data.

Comparisons between the traverse data obtained by the water company at regular intervals over a number of years appear to indicate that the velocity profile changes quite considerably. One suggestion for this is the possibility that the flow profile is continually changing from second to second. Although a degree of variability can be expected, even in a fully developed profile, it was considered that this transient effect may be so severe that difficulty would be experienced by those performing the traverse to obtain a repeatable velocity profile. There was however very limited repeat data available to indicate if this was in fact the case. The computer simulation was adapted in order to model the transient nature of the flow. The results indicated that there is indeed a substantial transient effect and it is concluded that this is the most likely reason for the poor comparison between the velocity profiles.

A number of suggestions for further investigation are made, including the need to perform a focussed experimental investigation on site. A number of key issues need to be addressed including: (1) determining the repeatability of the profiles by performing a number of traverses one after the other, (2) examining if the profiles vary with flowrate by traversing at different times of the day, and (3) normalising the probe data with another signal such as the second probe or the meter under test, in order to help eliminate the detrimental influence of fluctuations in the flowrate during the traverse. In conjunction, it would also be useful to investigate the data acquisition and signal processing being carried out by the probe software.

CONTENTS

E.1 INTRODUCTION

Insertion probes are used extensively throughout this water company as a means of performing meter verifications. A number of point velocity measurements are made across a diameter, and data integrated to establish the mean flow velocity. The comparison of this value with the value generated by the meter being verified, (typically a permanently installed electromagnetic meter), gives an indication of how accurately the electromagnetic flowmeter is measuring the true flow.

A comprehensive program of meter verifications has been established by the water company over the last 6 years or so, with such meter verifications being performed at regular intervals. Overall, their experience is that the probe traversing technique is a reliable and repeatable method of verifying the performance of flowmetering devices.

Having said this, however, they were aware that the verifications being performed at a number of sites with a particular type of installation were failing to meet their expectations. The purpose of this case study is to examine one such installation in some detail and determine the reasons why this water company is having difficulty verifying these meters to the required level.

The funding for this research was provided by the UK's Department of Trade and Industry through the NMSPU (National Measurement System Policy Unit) 1999-2002 Flow Programme, together with co-funding from a number of water companies: Anglian Water, Dwr Cymru, Northumbrian Water, Southern Water, Thames Water and Yorkshire Water. The major advantage to be gained from this collaboration with the water companies is the direction and support they have provided, ensuring that the research is carried out with a focus on issues of particular industrial relevance. A major part of this project was to undertake a number of case studies and this report presents the findings from one such study carried out for one of the water companies.

E.2 THE INSTALLATION

The site of interest is a reservoir where 3 separate branches of supply mains are metered with permanently installed electromagnetic meters. Each of these installations would normally be designed so that the meter is located in the main with a bypass, (together with associated valves), fitted around it. If required, the bypass could be opened, isolating the electromagnetic meter, enabling the meter to be serviced (or even removed) without disruption to the supply. The difference with the electromagnetic meters at this particular site is that each meter is installed in the bypass and the bypasses have a reduced diameter. The decision to install a reduced diameter bypass was based on a number of benefits:- Increased mean flow velocity making the electromagnetic meter potentially more accurate, reduced pipework required to maintain the required straight upstream and downstream lengths from the meter, reduced excavation work and costs.

A block diagram showing the typical installation detail is provided in Figure E.1. Here, it can be seen that the traversing point is located 4.5 m downstream, which represents around 10 diameters of the 18" pipe.

E.2.1 The Problem

The water company's experience with the meter verifications being performed at this site using the probe traversing technique is disappointing. From experience at other sites, where meters are not located in the bypass, they would expect a comparison of the mean probe velocity with the electromagnetic reading to be within 5%. Typically, comparisons at the site showed discrepancies of the order of 8, 12 and even as high as 20%. It would be normal practice following a first verification to adjust the electromagnetic meter on the basis that the probe result was the 'true' flowrate. However, even if an adjustment was made to account for such a large discrepancy, the water company were finding on repeat visits to this site, say a year later, that the electromagnetic meter was often still misreading by the same order of magnitude. This is very much contrary to their experience and hence the reason for this case study.

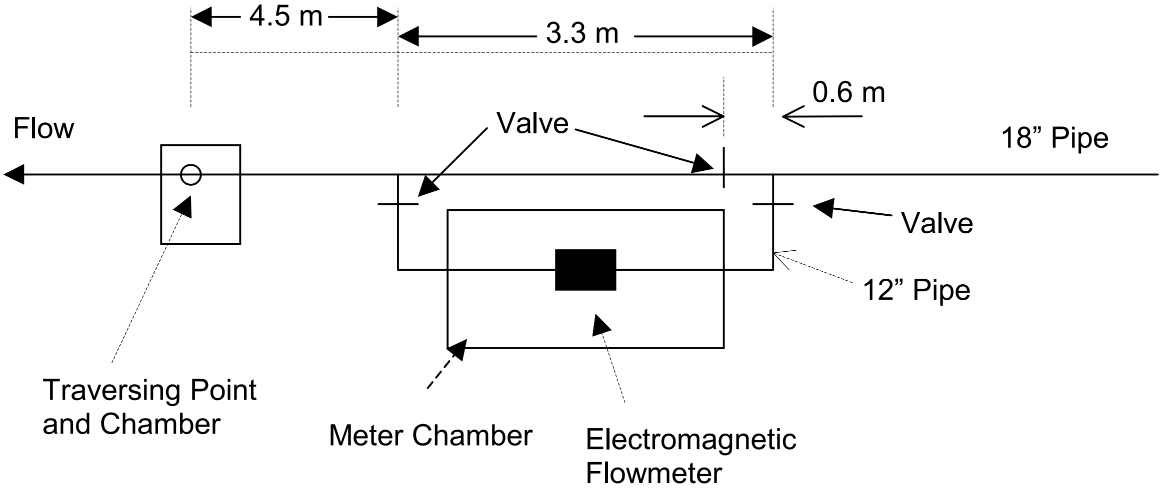


Figure E.1 Reservoir Meter Showing Traversing Point

E.3 VELOCITY PROFILE ERRORS

During a probe traverse, a number of point velocity measurements are made, and these are integrated to establish the mean flow rate. The water company typically measure 7, 9, 11 or 13 points across the diameter (depending on pipe size) and associated with taking a finite number of points across the traverse there is an error related to the integration. Generally speaking, multiple traverses with many points on each traverse will result in a lower error.

As described in Section E.1, the water company's experience is that probe traversing is a reliable and repeatable method of verifying the performance of flowmetering devices. On this basis it was suggested that the reason for the major discrepancies may relate to the traverse being carried out through a flow which is highly disturbed due to the two bends in the bypass. Also, there is an issue with regards to how many points are taken across the traverse, and whether increased points would improve the results.

It was decided to simulate the installation shown in Figure E.1 using Computational Fluid Dynamics (CFD). The extent to which the axisymmetric nature of the flow was contributing to the discrepancy between the probe and electromagnetic meter results could then be quantified. The procedure was first to take a virtual traverse of the simulated solution through the fully developed velocity profile in the 18” pipe (inlet) and integrate these point velocities in order to determine the mean flow rate. The same procedure was then carried out at the probe traversing point on the model (outlet) and the mean flowrate at this location calculated. The difference in these results represents an attempt at quantifying the installation effect error. Since these two integrated velocities are each calculated in the same manner this comparison is being conducted on a like-with-like basis. In other words, errors associated with the integration technique itself will tend to cancel out.

If this error could be shown to be relatively large, i.e. of the order of 10%, then this would allow the water company to make an informed judgement as to the likely misreading of the probe measurements. This in turn would justify an allowance to be made for this error and so any adjustments made to the electromagnetic meter could be made with this in mind. On the other hand, if the affect of the installation was shown to be minimal, i.e. the error was calculated to be relatively small, say less than 6%, then another explanation for the high errors experienced by the water company would be required.

Before going on to present the results of this analysis, the following describes the CFD modelling.

E.4 METHOD: FLOW SIMULATION AND ANALYSIS

E.4.1 CFD Simulation Parameters

This work used the Fluent 5.4 CFD software. This software has been used at NEL to investigate numerous installation effects on different types of flowmeter. The parameters chosen were based on previous experience of the optimum parameters for this type of work.

The main simulation parameters are listed below:

- Fluid (water) density = 1000 kg/m^3;
- Fluid viscosity = 0.001 Pascal Seconds;
- A fully developed velocity and turbulence profile was defined at the inlet with a mean inlet velocity[1] of 0.4 m/s;
- A zero normal gradient outflow boundary condition was defined;
- Turbulence effects were accounted for with a Reynolds Stress turbulence model;
- QUICK discretisation was used on all equations;
- Except when specified, the flow was assumed to be steady state (invariant with time). A 1st order implicit differencing scheme was used for transient simulations.

[1] Chosen to reflect the same mean flow rate at this location as measured with a typical probe traverse.

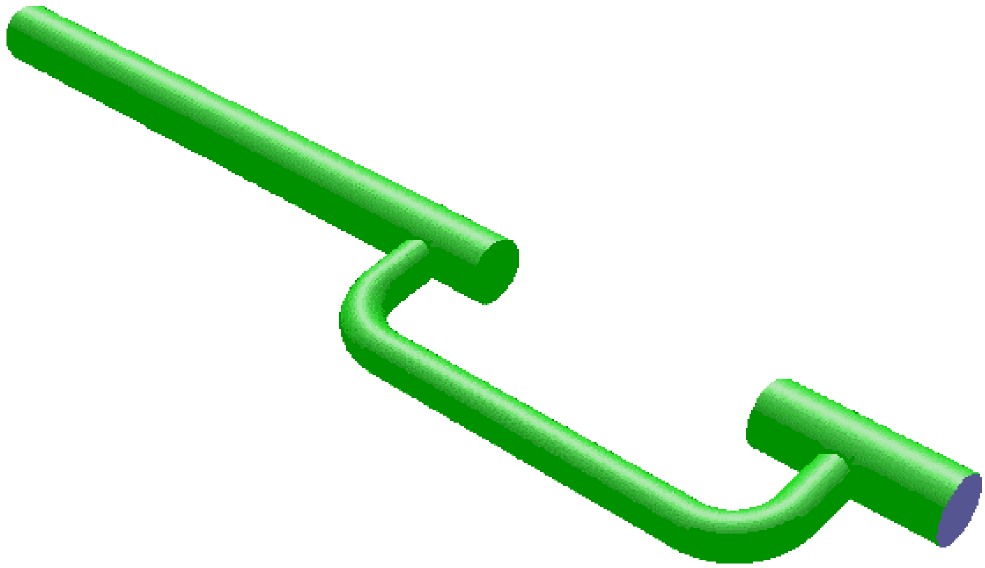


Figure E.2 The Computational Domain

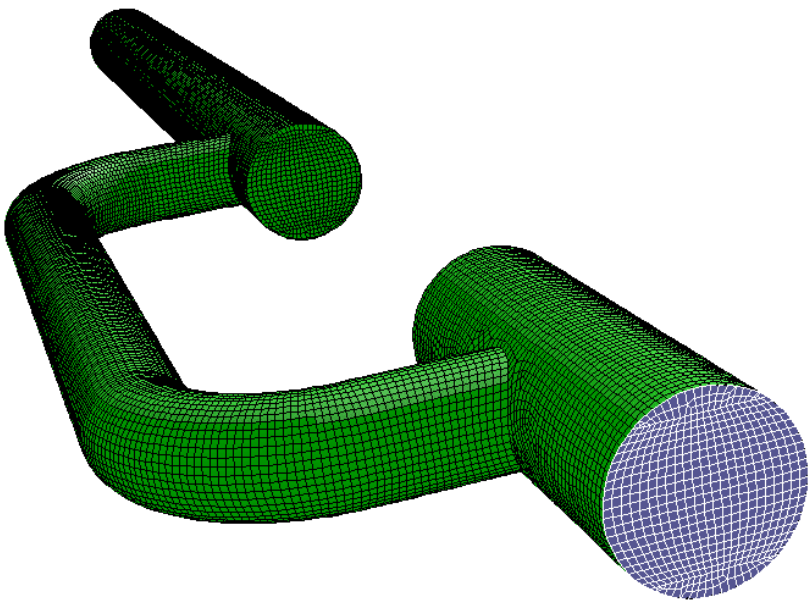


Figure E.3 A Typical Computational Mesh

Figure E.2 shows the geometry of the pipework typically defined in the simulations. The blue patch represents the inlet. The larger 18" pipe was terminated at the closed valve, forcing flow through the bypass. The flow then returned to the large pipe to pass through a straight section of approximately 10D before leaving the domain. The area of stagnant fluid between the bypass outlet and the valve in the 18" inlet section was not modelled. Figure E.3 shows a typical computational mesh.

Fluent has a facility that allows predicted values to be extracted from the CFD simulation along arbitrary lines defined by the user in the simulated pipework. This was used to represent the data extracted in the traverse measurements. However, it should be appreciated that data extracted in this manner represents an instantaneous traverse. In time varying flows no time averaging occurs, as would happen in reality.

It is noted, from discussion with the water company, that the time taken to perform a traverse is typically 10 to 12 minutes.

E.4.2 Results of the Flow Simulations

Early simulations assumed that the flow was steady state, i.e. it did not change with time. In this case the match between the CFD predictions and the measured probe data was not particularly good. Further work looked at the possibility that a partially closed valve or transient flow behaviour could account for the discrepancy between the predictions and measurements. The latter case produced the most convincing results.

This section presents the results of the work in the order in which it was executed: simple steady state models are discussed first, then models that account for valve closure and then finally the results from a transient simulation are described.

E.4.3 Measured Data

Figure E.4 shows velocity profiles from vertical and horizontal traverses taken on by the Water Company different days over about one year. In Figure E.5 these values have been normalised by the mean velocity to account for the fact that the volumetric flow rate varied between measurements.

Both vertical and horizontal profiles take a roughly flattened parabolic shape with an apparent random variation of about +/- 2.5%.

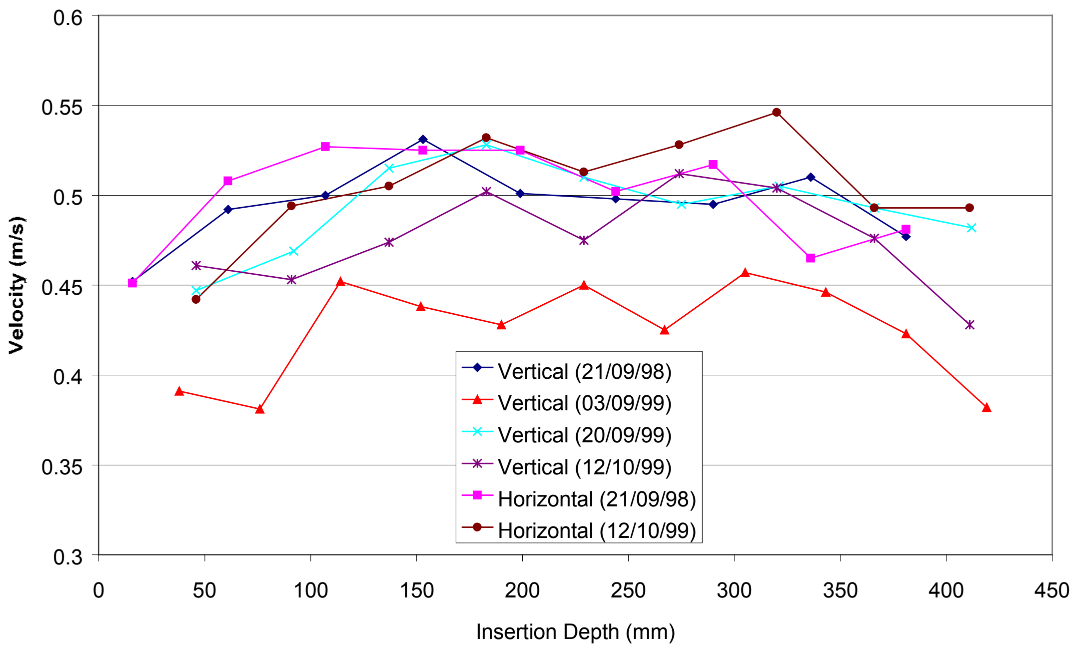


Figure E.4 Measured Velocity Profiles Using Probe

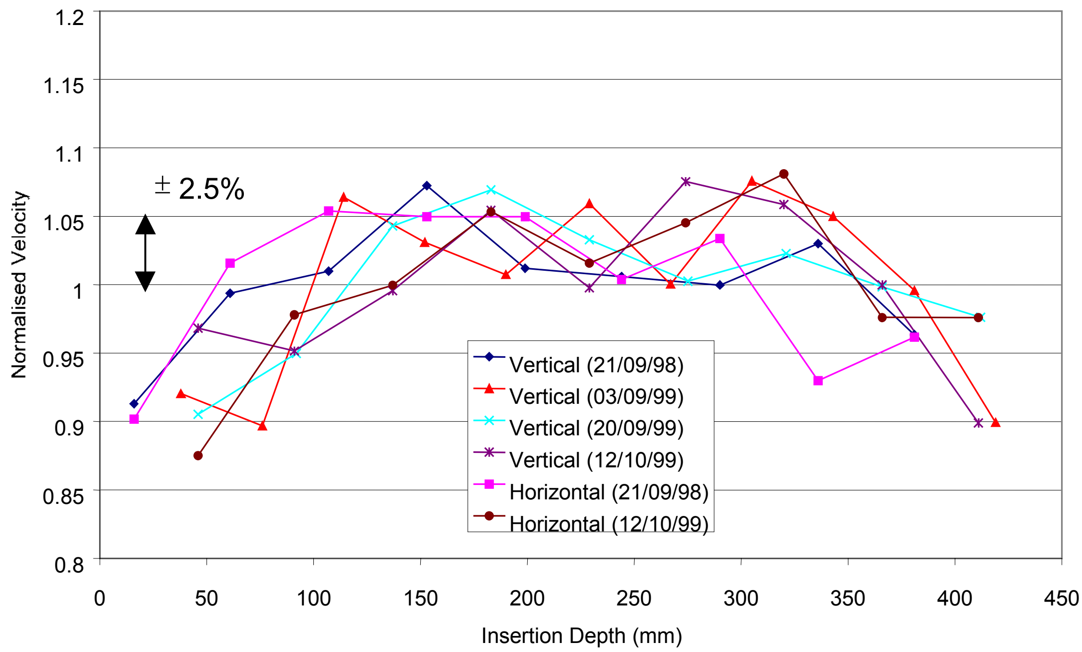


Figure E.5 Normalised Probe Profiles

E.4.4 Steady State Simulations

The first simulation used the mesh shown in Figure E.3. Figures E.6 and E.7 illustrate the flow behaviour seen in the pipework. Figure E.6 shows that velocity flow through the bypass is fastest on the inside surface of both bends. When the flow leaves the bypass it impacts on the wall of the main line causing a re-circulating zone (blue) immediately downstream of the tee and an elevated velocity to one side of the pipe. The blue re-circulation zone can also be seen just downstream of the tee in Figure E.7.

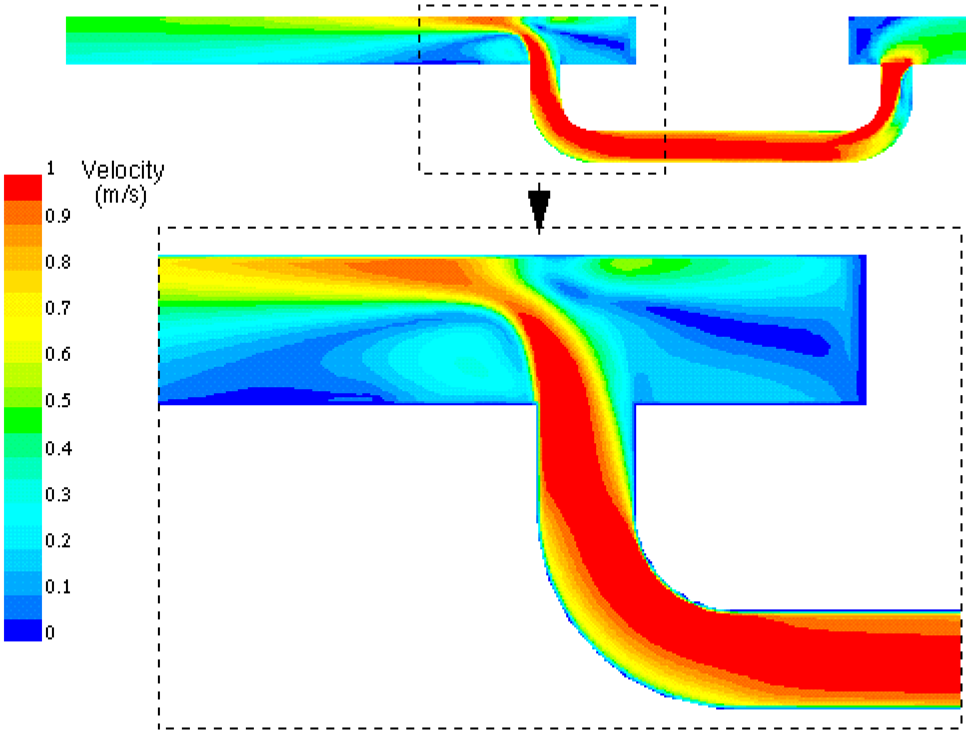


Figure E.6 **Contours of Velocity Magnitude on the Centre Plane of the Installation**

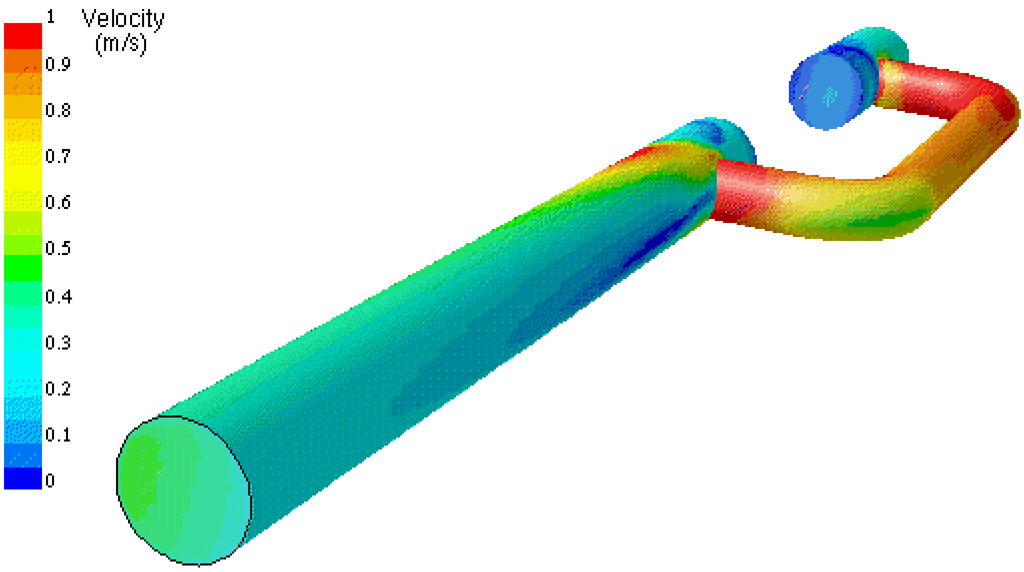


Figure E.7 **Contours of Velocity Magnitude Near the Pipe Walls From the Original CFD Simulation**

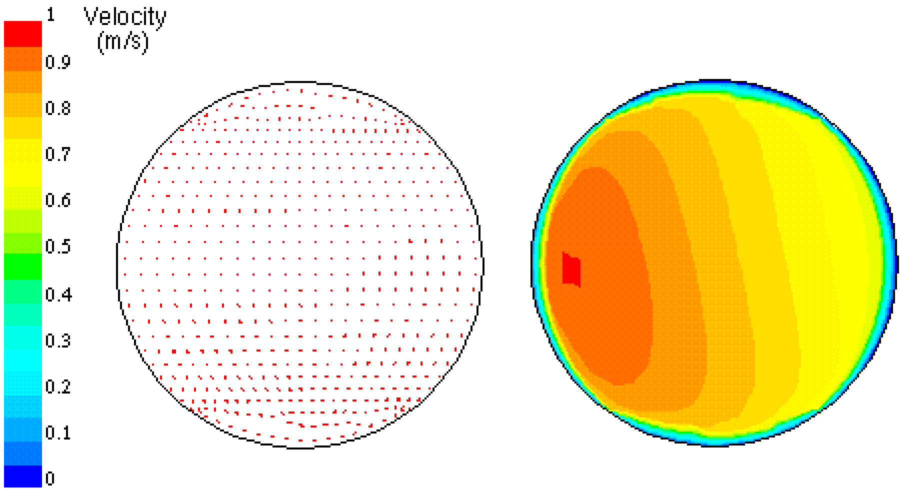


Figure E.8 Transverse Velocity Vectors (left) and Axial Velocity Contours (right) on the Plane of the Traverse From the Original CFD Simulation

Velocity vectors and contours taken on the plane of the traverse (Figure E.8) show that swirl has decayed to negligible levels at the traverse position, but the axial velocity profile is still skewed to one side of the pipe. The axial velocity profile is also slightly asymmetrical about the horizontal plane. This is an unexpected result and is believed to be associated with numerical errors within the CFD simulation. Subsequently the original computational mesh was bisected with a symmetry plane defined about the horizontal mid-plane. Re-running the simulation with this new mesh forced a symmetrical solution. The predicted conditions at the traverse for this "enforced symmetrical solution", shown in Figure E.9, are very similar to the original predictions shown in Figure E.8.

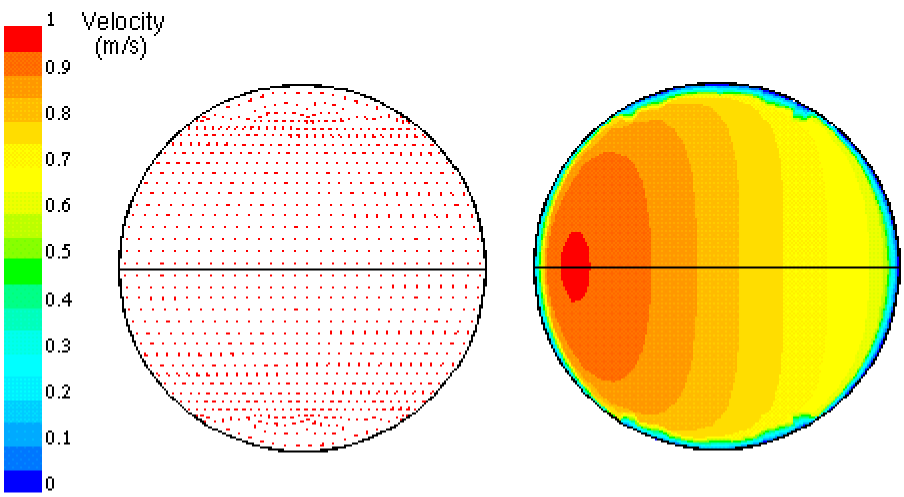


Figure E.9 Transverse Velocity Vectors (left) and Axial Velocity Contours (right) on the Plane of the Traverse for the Simulation with Enforced Symmetry. (The symmetry plane is shown as a black line).

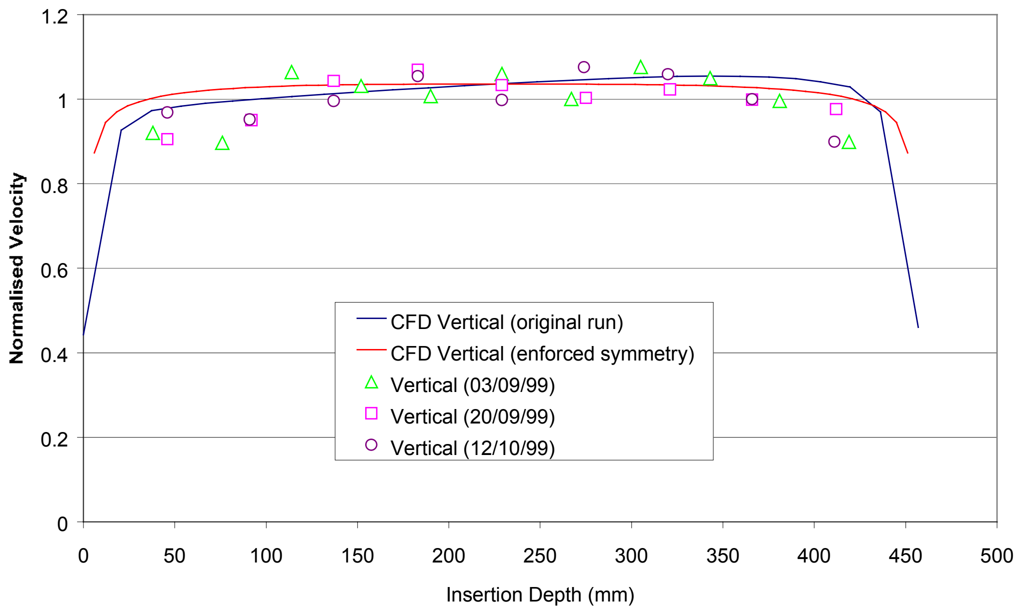


Figure E.10 Predicted and Measured Vertical Traverse Profiles for the First Two CFD simulations

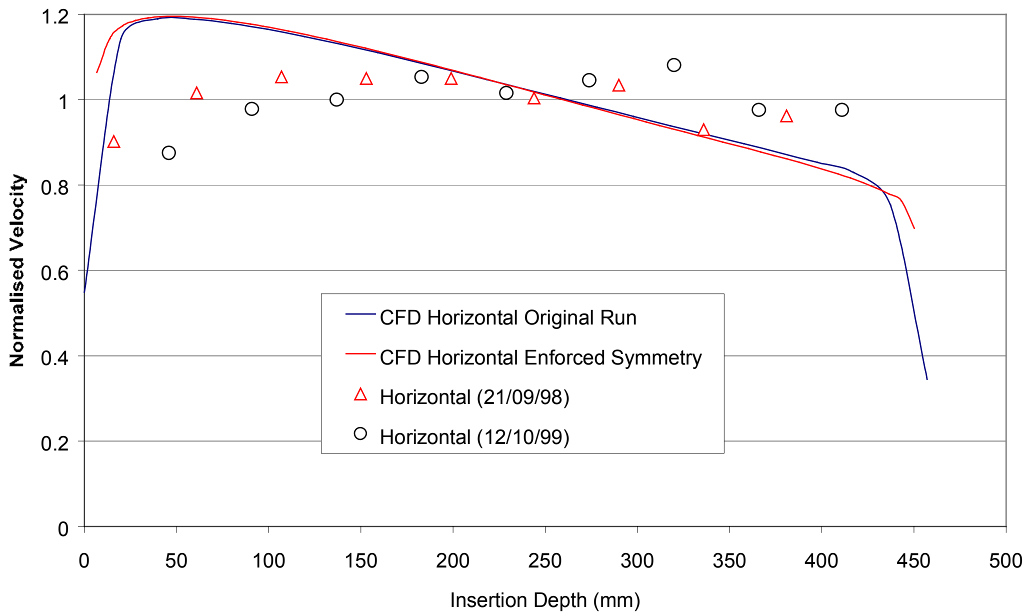


Figure E.11 Predicted and Measured Horizontal Traverse Profiles for the First Two CFD Simulations

Figures E.10 and E.11 compare predicted traverse profiles of the first two CFD simulations against the measured data. It can be clearly seen that the symmetrical and asymmetrical traverse match quite closely. There is reasonable agreement between the measured and simulated values for the vertical traverse, but it is clear from Figure E.11 that the skewed profile predicted by the CFD does not occur in reality.

E.4.5 Comparing Integrated Profiles At the Inlet and Outlet of the Installation

As described in Section E.3, virtual traverses were performed across the simulated flows and the point velocities integrated in order to calculate the mean flow velocity. The first traverse was made on the fully developed flow entering the installation (inlet). The CFD model was set up, as described in Section E.4.1, to have a mean flow velocity of 0.4 m/s. This is the baseline condition from which changes are measured. The second virtual traverse was performed in the model at the point where the actual tapping point is located (outlet). Any discrepancy between these two integrated results is assumed to represent the error introduced by the installation for whatever number of traversing points have been used. As more traversing points are taken the error would reduce. On this basis, and in order to check the model, a useful starting point was to compare the integrated solutions from the inlet and outlet traverses using all the available data in the model.

E.4.5.1 Verification of the Model: 34 Point Virtual Traverse

The first stage was to take a traverse across a diameter using all the available point velocity information. The mesh used in the model with the enforced symmetry was very fine and generated 34 equally spaced velocity point measurements across the diameter. The integration of these data resulted in a mean flow velocity of 0.399 m/s which is just 0.25% less than the 0.4 m/s set up in the model. A similar integration of the 34 velocity points on the outlet side of the installation also resulted with a mean flow velocity of 0.399 m/s. This comparison between inlet and outlet integrations is as expected. Due to the detailed knowledge of the velocity profiles, and the model having to assume conservation of mass, these mean velocities should be the same.

E.4.5.2 Virtual Traverses: 7, 9 and 11 Points

The next stage was to perform 7, 9 and 11 point virtual traverses across the inlet and outlet sides of the installation. Any differences between these respective mean velocities is assumed to represent the error introduced by the affect of the installation. A summary of the results obtained from this analysis is provided in Table E.1.

E.4.5.3 Conclusions from Virtual Traverses

As described in Section E.3, the aim in this analysis is to quantify the error introduced by the installation effect when performing a probe traverse. If this error could be shown to be comparable in magnitude to the discrepancies experienced by the water company then this would help explain why the errors appeared so large and would allow suitable judgements to be made regarding any potential meter adjustments.

From Table E.1, the maximum error introduced by the installation is with a 7 point traverse, where an error of around 3% has been calculated. This is somewhere short of the 8, 12 or even 20% discrepancies highlighted in Section E.2.1. It is therefore concluded that the error introduced by the installation effect in terms of the integration of the axisymmetric profile is unlikely to be the entire cause of the discrepancies experienced by the water company.

On this basis, the CFD simulation was now modified in order to examine if having the valves in the system slightly closed could generate a sufficiently disturbed profile.

Here, the aim is to see if the errors calculated above would increase to a level more comparable with the experience of the water company (8 to 20%).

It is highlighted that the analysis presented here compares the integrated flow profiles on either side of the bypass. For the installation shown in Figure E.1, no attempt has been made throughout this work to attempt to assess the affect that the installation may be having on the performance of the electromagnetic flowmeter. There is approximately 5 diameters of straight upstream and downstream length either side of the meter and, compared to the quoted discrepancies of 8, 12 and 20%, the error in the electromagnetic meter readings due to the installation are likely to be substantially less.

Table E.1 Estimation of Installation Errors

Integrated Mean Flow	Mean Velocity (m/s)	Error (%)	Average of Vertical or Horizontal (m/s)	Average Error (%)
- with 34 pt Vert. Data on Inlet	0.3988	-	-	-
- with 34 pt Horiz. Data on Inlet	0.3993	-	0.3991	-
- with 34 pt Vert. Data on Outlet	0.3989	-	-	-
- with 34 pt Vert. Data on Outlet	0.3986	-	0.3988	-0.08
- with 7pt Vert. Traverse Inlet	0.3995	-	-	-
- with 7pt Horiz. Traverse Inlet	0.4001	-	0.3998	-
- with 7pt Vert. Traverse Outlet	0.3879	-2.90	-	-
- with 7pt Horiz. Traverse Outlet	0.3879	-3.05	0.3879	-2.98
- with 9pt Vert. Traverse Inlet	0.3994	-	-	-
- with 9pt Horiz. Traverse Inlet	0.4001	-	0.3998	-
- with 9pt Vert. Traverse Outlet	0.3908	-2.15	-	-
- with 9pt Horiz. Traverse Outlet	0.3907	-2.35	0.3908	-2.25
- with 11pt Vert. Traverse Inlet	0.3994	-	-	-
- with 11pt Horiz. Traverse Inlet	0.4000	-	0.3997	-
- with 11pt Vert. Traverse Outlet	0.3927	-1.68	-	-
- with 11pt Horiz. Traverse Outlet	0.3926	-1.85	0.3927	-1.77

E.4.6 Steady State Simulations Accounting for Valve Closure

From the analysis described in Sections E.4.5 to E.4.5.3, it is clear that the inlet and outlet integrations are not producing large enough differences to account for the discrepancies observed between the probe and electromagnetic meter measurements. Similarly, Figures E.10 and E.11 show that the CFD simulations described so far have failed to adequately reproduce the flow behaviour occurring in the field. It was thought possible that this discrepancy could be associated with the gate valves at the inlet and outlet to the bypass. Operational evidence suggested that these valves were fully open during the traverse. However, it is possible, in certain designs, that such valves can remain slightly closed even when correctly adjusted into the fully open position.

Previous experience suggested that a partially closed valve would generate swirl and this swirl could act to flatten out the measured axial velocity profile, thus explaining the discrepancy. The degree of valve closure required to cause swirl was not known. In order to investigate this effect two additional simulations were run with a section representing a partially closed valve included in the model.

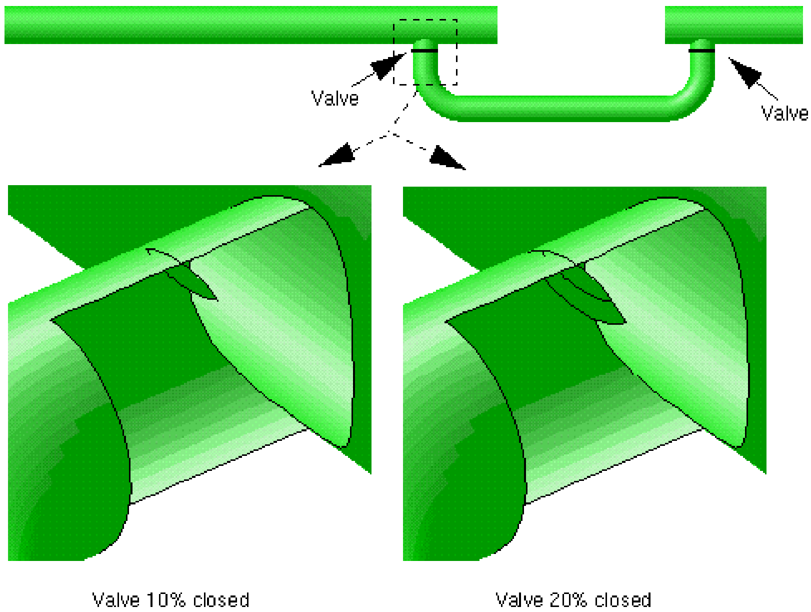


Figure E.12 The Computational Domain and the Section Representing a Partially Closed Valve

Two valves were included in the simulated installation at the bypass inlet and outlet. These were represented as flat circular plates intruding into the 12" pipe as illustrated in Figure E.12. With both valves 10% closed very little difference is seen (c.f. Figures E.13 and E.8). However, if the valves are 20% closed a significant degree of swirl is generated. The spiralling nature of the flow can be seen in Figure E.14 and the single vortex swirl is clearly shown in Figure E.15. However, the axial velocity profile is still highly skewed, unlike the measured values. This suggests that valve closure does not adequately explain the discrepancy between the CFD and probe measurements. For this reason no attempt has been made to repeat the virtual traversing exercises described in Sections E.4.5 to E.4.5.3.

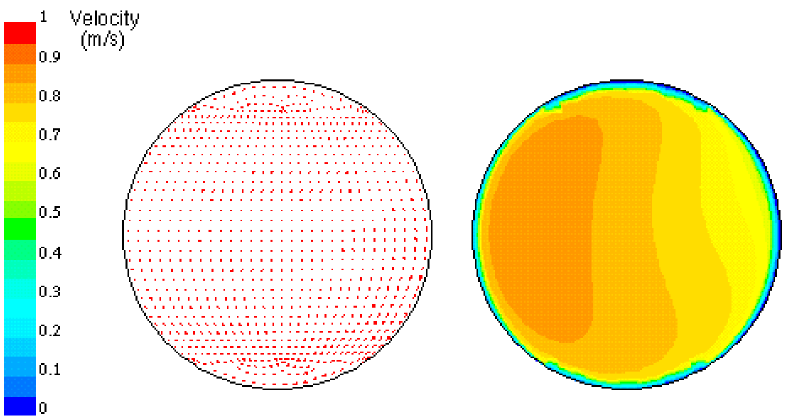


Figure E.13 Transverse Velocity Vectors (left) and Axial Velocity Contours (right) on the Plane of the Traverse for a 10% Closed Valves

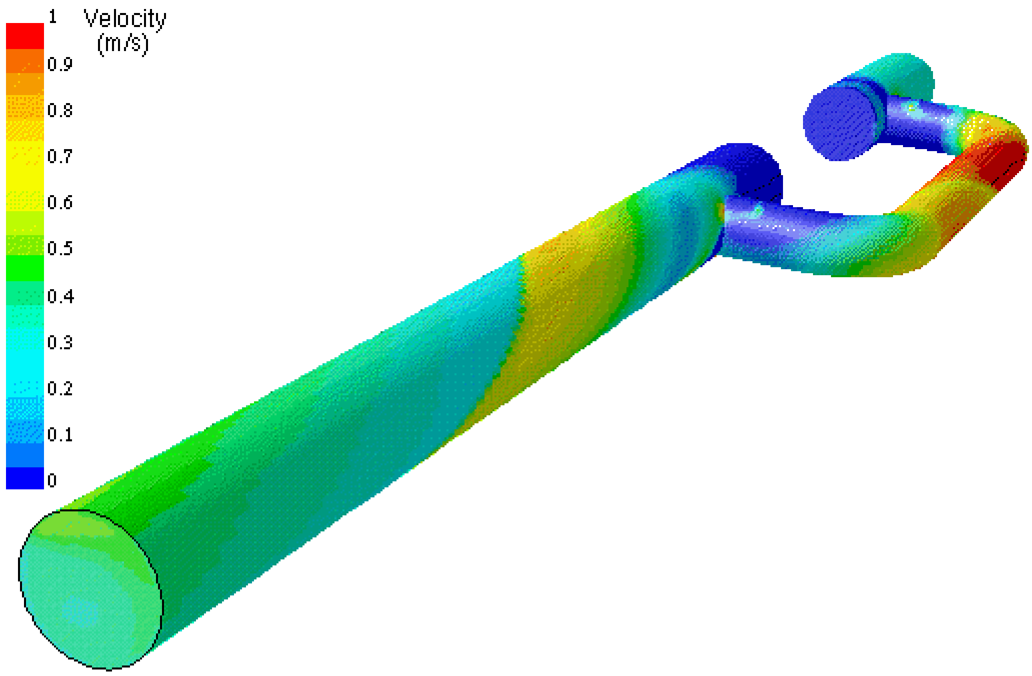


Figure E.14 Contours of Velocity Magnitude Near the Pipe Walls From for Valves 20% Closed

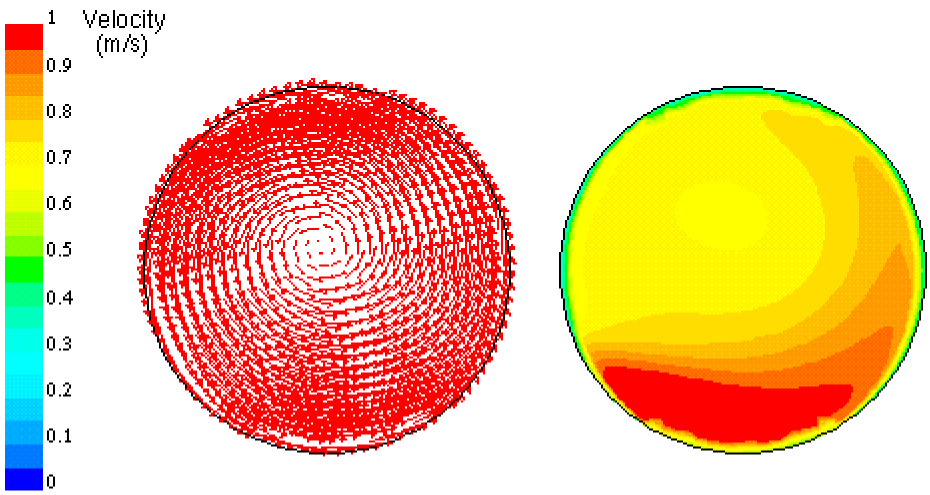


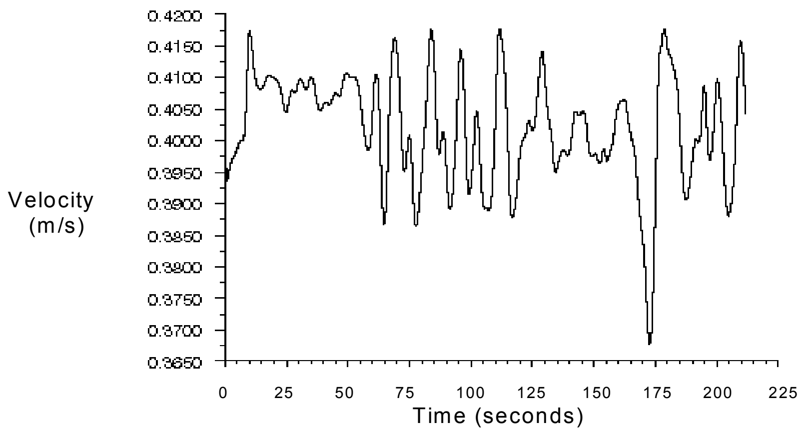
Figure E.15 Transverse Velocity Vectors (left) and Axial Velocity Contours (right) on the Plane of the Traverse for Valves 20% Closed

E.4.7 Transient Simulation

A second potential cause of the disagreement between the CFD and measured data was the assumption made in the CFD simulations that the flow was steady state. To test this a final CFD simulation was run in which the flow was allowed to vary with time. As transient simulations can be quite computationally expensive, this simulation was run using a coarser mesh than in previous simulations. This may have compromised the absolute accuracy of the simulation. However, the primary aim of this simulation was to identify whether transient flow behaviour could have occurred in this instance rather than to produce a particularly accurate solution. A coarser mesh than that shown in Figure E.3 was therefore deemed to be sufficient for this purpose. It is emphasised that the partially closed gate valves introduced to the model (Section E.4.6) were removed from this transient analysis.

Figures E.16a and E.16b show the variation of predicted flow velocity with time at two points on the horizontal traverse line. It is clear that the velocity does indeed fluctuate with time. The fluctuations between 0 seconds and 60 seconds are associated with the solution process and are not believed to represent physically realistic behaviour. However, after 60 seconds the flow behaviour is believed to be realistic. The fluctuations have a predicted period of about 12 seconds (0.08 Hz frequency) and an amplitude of between about 0.015 m/s and 0.04 m/s (+/- 4 to +/- 10% of the mean velocity). Discussed in Section E.5.2.2 is the need for careful logging and analysis of the probe data in order to determine the extent to which the transient fluctuations are the source of the problem.

a) Depth = 79mm



b) Depth 379mm

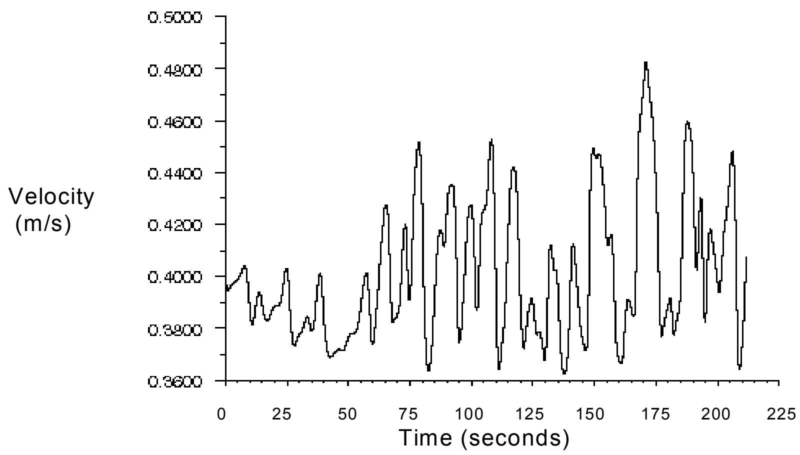
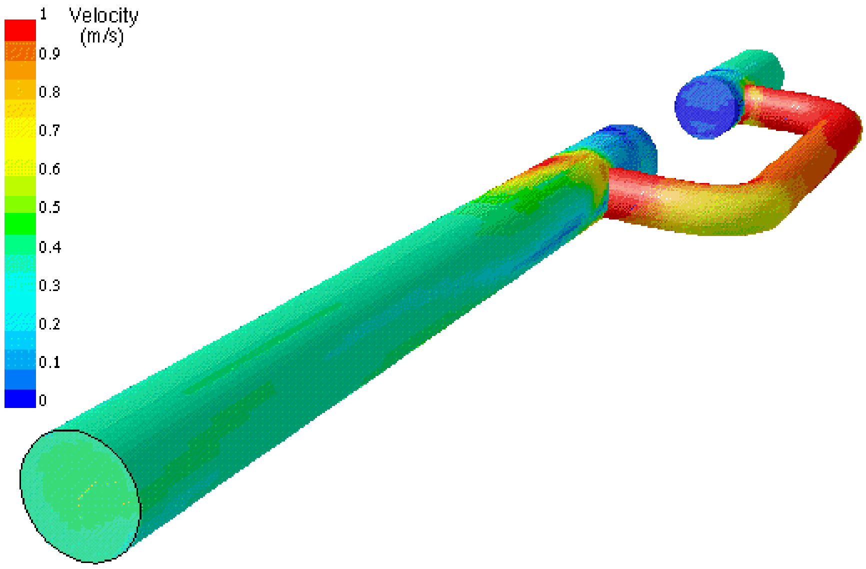
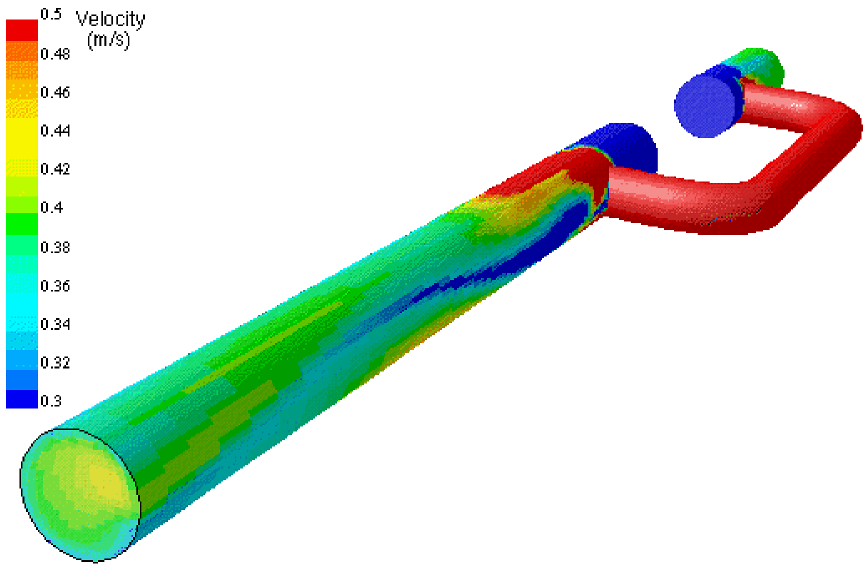


Figure E.16 Predicted Axial Velocity at Two Points on the Horizontal Traverse Line

Figure E.17 shows the source of this fluctuation. In Figure E.17 the (blue) re-circulation zone downstream of the tee is sinusoidal in shape. This is different to previous steady state cases (c.f. with Figure E.7). As time progresses this sinusoidal shape is seen to "snake" or move in the manner of a flag in the breeze. This unsteady behaviour of the flow separation zone downstream of the tee propagates as far as the traverse line generating velocity variations at the measuring points.



a) Scales as in previous figures



b) Scale = 0.3 to 0.5 m/s to illustrate behaviour of the re-circulating zone

Figure E.17 Contours of Velocity Magnitude Near the Pipe Walls for the Transient CFD Simulation at a time of 336 seconds

Figure E.18 shows a snap shot in time of the velocity profile in the plane of the traverse. The velocity profile is significantly different from that seen in the steady state solutions. Swirl is now present in the measurement plane and the axial velocity profile is flatter than in the steady state cases.

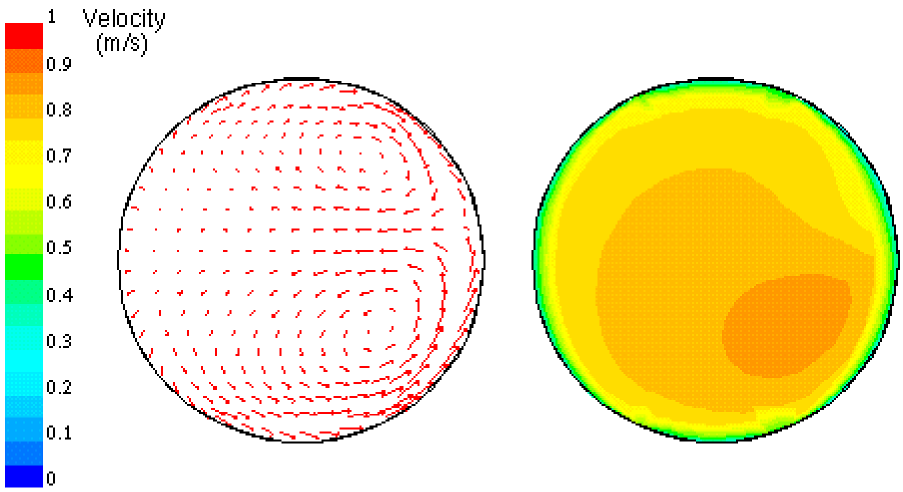


Figure E.18 Transverse Velocity Vectors (left) and Axial Velocity Contours (right) on the Plane of the Traverse for the Transient CFD Simulation

Plotting the velocity profiles against the experimental data (Figures E.19 and E.20) shows that the fluctuations in the velocity profile mostly lie within the band defined by the measured data, and in this respect the agreement between the CFD and probe measurements is good.

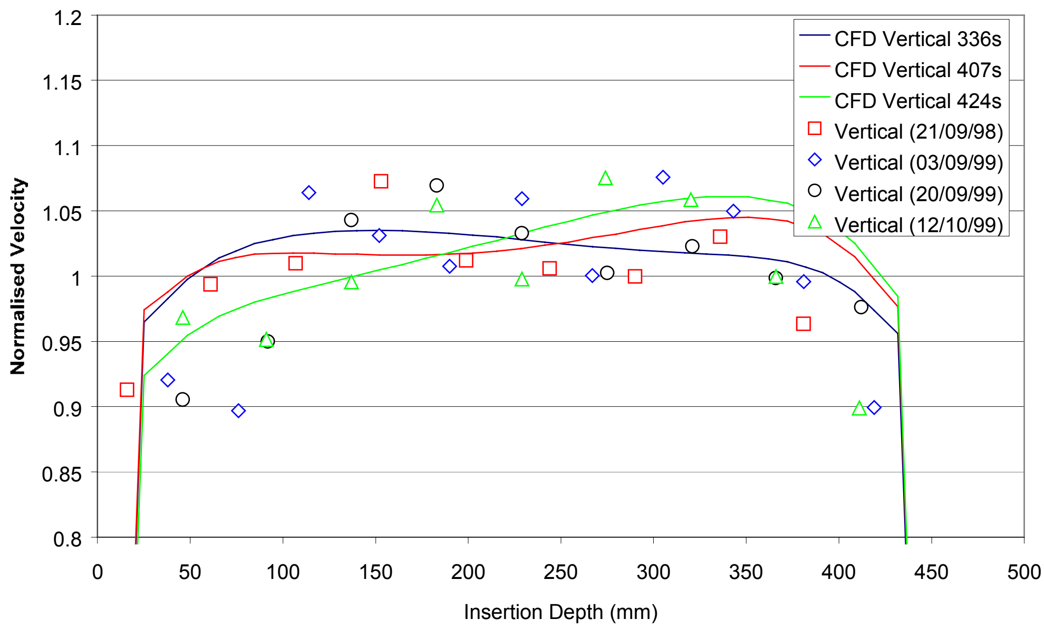


Figure E.19 Predicted and Measured Vertical Traverse Profiles for the Transient CFD Simulation

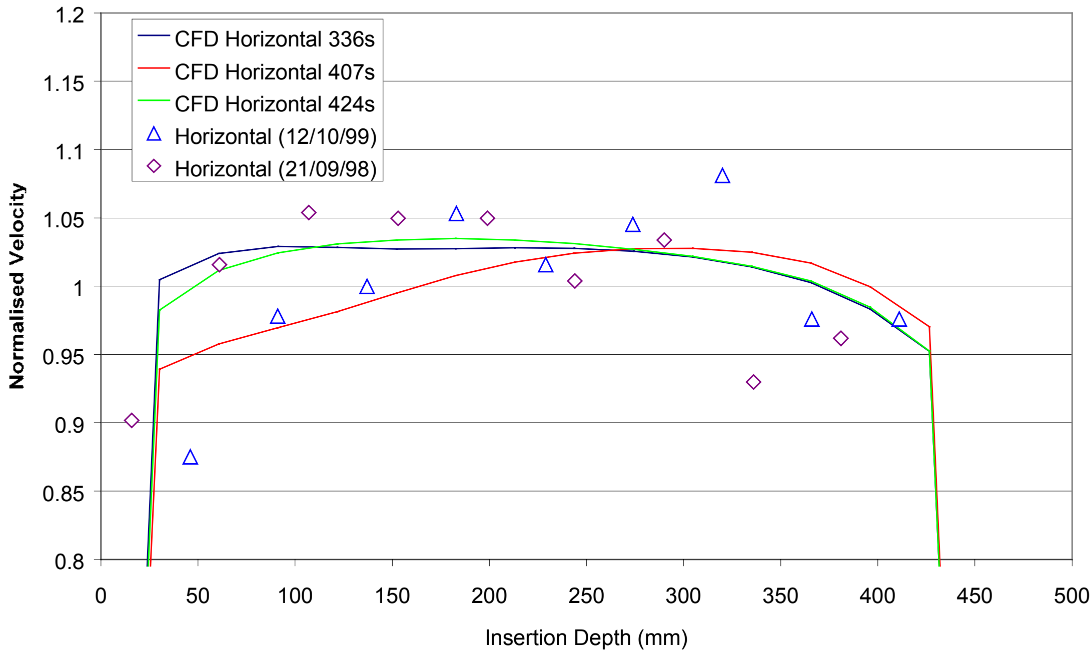


Figure E.20 Predicted and Measured Horizontal Traverse Profiles for the Transient CFD Simulation

However, when comparing these values it should be borne in mind that the CFD profiles represent measurements taken instantaneously whereas each probe measurement point represents an average of a number of multiple measurements taken by the sensing head and associated instrumentation. The effect of averaging multiple point measurements will be to reduce the amplitude of the perceived fluctuations (provided the measurement frequency is high enough and the measurement period is long enough). This may be one reason why the predicted fluctuation amplitude of between 4 and 10% is greater than the apparent fluctuation amplitude in the measured values (about 2.5%).

E.4.8 Flowrate Variation During the Traverse

During a traverse it is recognised that this procedure may take in the order of 10 to 12 minutes to perform. The potential for significant variations in flowrate throughout such a small time frame is illustrated in Figure E.21. Here, the data acquired by an electromagnetic meter at a different reservoir, over a period of 31 days, has been analysed. Every separate 15 minute period over the 31 days was averaged and results in an average daily usage for the month. Plotted alongside the daily usage is the standard deviation of each set of 15 minute data. Interestingly, the fluctuation in demand at 08:15, 12:45 and 17:45 throughout the month is noticeably quite small. Here, in percentage terms, the fluctuation in demand at these specific times is less than at other times.

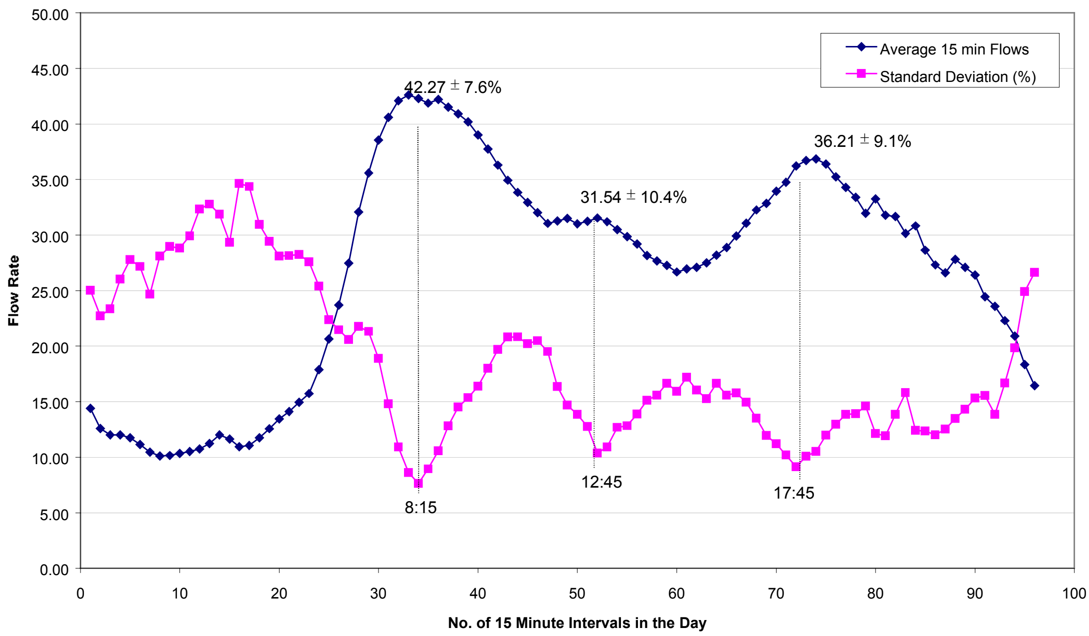


Figure E.21 Typical Average 15 Minute Flows Throughout the Day

E.5 DISCUSSION AND CONCLUSIONS

Before going on to discuss the conclusions and recommendations emanating from this study it is first important to describe the flow verification procedures currently adopted by the water company in more detail.

E.5.1 Probe Verification: Current Practice

The procedures adopted by the water company when performing a probe traverse are as follows:

- A single or pair of traverses (horizontal and vertical) is performed and the average mean flowrate determined using the proprietary probe software;
- During this traverse, no attempt is made to normalise the signal for any fluctuations that will occur in the flow during this operation;
- The probe is inserted to the mains centreline;
- During a period of approximately 24 hours, the output data from the probe together with the data from the meter being verified are logged;
- This data is plotted against each other and the extent to which the line does not exactly fit a *y=x* line is resolved, i.e. the resultant line is resolved to the y=mx+c equation allowing the 'offset' and 'range' errors, to be established. If required, the meter being verified is suitably adjusted.

E.5.2 Potential Improvements to Probe Traversing Procedures

Following the analysis presented in this case study, three key issues are highlighted to be addressed, in order to increase the effectiveness of the probe profiling and verification procedures carried out at this site. Firstly, as discussed in Section E.5.2.1, is the potential for profile variations with flowrate. Secondly, as discussed in

Section E.5.2.2, are the issues relating to the transient fluctuations in the flow which have been predicted with the CFD to have a cyclic period of around 12 seconds. Thirdly, as discussed in Section E.5.2.3, are the issues relating to the potential for the mean flowrate to change during the time taken to carry out the traverse (around 10 to 12 minutes). It is also summarised in Section E.5.2.4 that many of the problems introduced by the installation could be overcome by simply installing a tapping location upstream of the installation.

E.5.2.1 Mean Flowrate Position

One key question which is required to be answered is the extent to which the velocity profile may vary with flowrate. If a mean flow velocity position was being assumed at a constant 'D/8' position then this could well result in the mean flow velocity position varying with demand. On the other hand, if a centreline velocity is being measured, as is this water company's standard practice, then a changing profile would be indicated by the profile factor (as calculated, for example, by the aquaprobe software) also changing.

This can only be determined by performing the traverse at a number of different times during the day, and preferably at periods where the flowrate is considered to be stable. The data shown in Figure E.21, for example, indicates that at this reservoir reasonably stable periods during the month being considered are: 01:00 to 04:00 Hrs; 07:45 to 08:45 Hrs; 11:30 to 13:00 Hrs and 14:30 to 15:15 Hrs.

Such an evaluation would allow an informed judgement to be made about whether there is indeed a repeatable flow profile at different flowrates and whether a single profile factor (or mean flow position) can be used at all times of the day to determine the mean flowrate.

E.5.2.2 Repeatability

The water company has in place a well established and systematic programme for performing meter verifications. This system utilises a number of specifically designed databases where information relating to the meter verifications is stored. However, there does appear to be little statistical cross comparison between the information being generated whilst in the field and the historically stored data. For example, it is unlikely that the variability in the velocity profiles at the site (see Figures E.10 and E.11), would have been identified as part of the water company's own rolling program of meter verifications.

As Figures E.10 and E.11 show, the shape of the velocity profiles generated from the traverse appear to show the relatively poor repeatability of the technique at this site. This being the case, it is not surprising that the comparison of the probe with the meter being verified is failing to meet required expectations.

As detailed in Section E.4.7, it is believed that even if the flow entering the installation has a constant mean flowrate, a major cause of the relatively poor definition of the velocity profile at the site is due to the transient nature of the flow variations. Here, the unsteady behaviour of the flow separation zone downstream of the tee propagates as far as the traversing point resulting in velocity variations at the measuring points. This raises issues with regards to the signal averaging procedures being carried out by the probe instrumentation. For example, it could be the case that the probe software has an upper limit on the variability that it will accept in the flowrate signal. Furthermore, it may be filtering out the peaks and the troughs generated by the transient fluctuations and so generate an unrepresentative average. This issue requires further investigation. Here, a system of logging un-averaged flowrate data from the probe at the site could be compared with similar data obtained at a site where the probe technique is known to be reliable. This would confirm, or otherwise, the theory that the profile at this site is suffering from transient fluctuations due to the installation effect.

The most critical element when verifying the performance of the meter under examination is the determination of which profile factor to apply to the centreline flow velocity in order to calculate the mean flowrate. If repeat probe traverses indicate significant variability in this profile factor, then it stands to reason that this variability directly affects the verification and any meter adjustments made on the back of the probe measurements. It is suggested that it would be very useful to investigate the issue of repeatability, perhaps taking several nominally identical traverses at similar times on consecutive days. This would then allow a range of profile factors to be identified and the resulting uncertainty due to this repeatability issue could be quantified. The potential for the flow profile to be affected by flowrate was discussed in Section E.5.2.1 and so the issue of repeatability may need also to be assessed at different flowrates.

E.5.2.3 Normalising the Probe Data

As detailed in Section E.5.2.1, the water company do not make any attempt to normalise the probe data for any fluctuations in the flow during the traverse. In the case of reservoir metering, as being examined here at this site, the flowrate is demand dependent. This means that only when the procedure of normalising the probe data with another signal (such as that of a second probe or of the meter under test) is carried out, can there be full confidence that the profile data is reliable.

It is concluded therefore that even if it assumed that there is a single mean flowrate position for different flowrates (Section E.6.2.1), it is still a requirement that the mean flow velocity during the time taken to carry out the traverse remains constant. This is unlikely to be the case (See Figure E.21) and so a process of normalising the probe data will be necessary to take into account such a changing mean velocity.

E.5.2.4 Changing the Location of the Probe Tapping Point

It should not be overlooked that one solution to the problem of the installation effect being discussed in this case study is to perform the probe traverse at a position upstream of the installation (assuming that a well developed profile is present). The installation of a further tapping location, together with additional chamber construction and so on, has obvious financial implications.

APPENDIX F

CASE STUDY REPORT: UNCERTAINTY ANALYSIS OF CLAMP-ON ULTRASONIC FLOWMETERS

EXECUTIVE SUMMARY – APPENDIX F

This report identifies and describes the sources of uncertainty that are associated with the application of clamp-on ultrasonic flowmeters. Furthermore, these uncertainties are quantified using theoretical techniques and where possible are backed up with reference to experimental results. This information will aid industrial users in allowing informed decisions to be made regarding both the use of the measuring instrument itself and operating procedures.

A critical issue in the assessment of flowrate using clamp-on ultrasonic meters is knowledge of, and proper use of, the pipe material and dimensional information. The resulting uncertainty in volumetric flowrate is twice the fractional uncertainty in the measurement of internal pipe diameter that is used to calculate cross-sectional-area i.e. 1 % uncertainty in pipe diameter becomes 2 % uncertainty in flowrate. Pipe and liner material properties and thickness must also be known accurately. Highlighted in this report is that care must be taken when attaching the transducers to the pipe.

Transit time and transit time difference measurements are also discussed. Here, although these measurements can be made accurately, they can still be prone to additional errors that are generally difficult to quantify. Delays in electronics, transducers and pipe walls, as well as timing resolution and zero-flow offset delays, contribute to these uncertainties.

Velocity profile effects are expressed as potentially the single largest source of uncertainty when using clamp-on ultrasonic meters. The results of a velocity profile sensitivity analysis is presented which summarises the results from a computational analysis of three path configurations and thirteen different two-dimensional velocity profiles. The results indicate that for most of the profiles considered, introducing a second diameter path measurement reduces the error considerably. This conclusion is backed up with experimental results from both single-path and dual-path meters positioned at varying diameters downstream of a single bend. The extent to which pipe roughness can influence the velocity profile error is also presented.

It is concluded that each of the different sources of uncertainty associated with clamp-on ultrasonic flowmetering can contribute to the overall uncertainty. It is therefore required that the determination of appropriate input values for each source of uncertainty be made depending on the particular conditions under which the measurements are taken. Under favourable conditions of application, a combined uncertainty of 2 – 5 % of reading could be expected.

CONTENTS

F.1 BACKGROUND

Clamp-on ultrasonic meters are considered to be unique in their ability to measure flow with little or no modification to existing pipes. They are used extensively in the water industry to provide measurements where there is no permanently installed metering and also to verify the accuracy of permanently installed meters such as electromagnetic meters. One water company, who regularly make use of such technology, have asked the National Engineering Laboratory (NEL) to undertake an uncertainty evaluation of these meters. This report summarises the findings of this work.

The funding for this research was provided by the UK's Department of Trade and Industry through the NMSPU (National Measurement System Policy Unit) 1999-2002 Flow Programme, together with co-funding from a number of water companies: Anglian Water, Dwr Cymru, Northumbrian Water, Southern Water, Thames Water and Yorkshire Water. The major advantage to be gained from this collaboration with the water companies is the direction and support they have provided, ensuring that the research is carried out with a focus on issues of particular industrial relevance. A major part of this project was to undertake a number of case studies and this report presents the findings from one such study carried out for one of the water companies.

F.2 INTRODUCTION

The clamp-on ultrasonic meters under consideration here are based on the transit time principle. These come in various forms including portable versions with keypad and local display, which can be used with a variety of transducers depending on the application. Two or four transducers are attached to the exterior surface of the pipe and act as both transmitters and receivers of ultrasound, which is transmitted through the pipe wall and the fluid at an oblique angle to the axis of the pipe. The principle of operation of these meters is detailed in Appendix F1.

The conversion of the ultrasonic signals is carried out in the meter's electronics. Most modern ultrasonic meters use sophisticated digital signal processing and microprocessor functions in an attempt to produce a more robust, accurate and flexible meter.

It is only ultrasonic transit times that are directly measured by the device. The other parameters in the flowrate equation are determined from look-up tables and user-input information regarding the pipe dimensions, pipe materials and fluid. The separation of the transducers is also determined from this information. Uncertainty in these input parameters therefore has a direct effect on the accuracy of the instrument. Specific pipe and transducer parameters must be entered into the meter's software or the measurement may not be possible or may be made with large uncertainty.

The performance of clamp-on ultrasonic meters can vary from manufacturer to manufacturer due to inherent design differences and manufacturing quality. It has been NEL's experience that the error in measurement by clamp-on ultrasonic transit time meters is in the region of 2 - 5% when set-up with due care and attention in suitable flow conditions. In general the performance of the meters tends to degrade as the velocity of the flow decreases. In available lab data the degradation in performance tends to become noticeable below approximately 0.5 m/s.

In this report an analytical approach to uncertainty and error analysis is combined with data from practical laboratory evaluations to give an insight into the performance that should be expected from clamp-on ultrasonic flowmeters.

F.3 UNCERTAINTY ANALYSIS

F.3.1 Determination of the Internal Pipe Diameter

It is shown in Appendix F1 that the uncertainty in volumetric flowrate is twice the fractional uncertainty in the internal pipe diameter. Errors in measurement of the pipe diameter produce a bias in the volumetric flowrate measurement that is independent of flowrate. An overestimation of diameter causes an over-reading of flowrate and vice versa.

The internal diameter of the pipe is normally calculated from a measurement of the circumference of the pipe and a measurement or estimation of the combined pipe wall and liner thickness. The user should use a calculator to ensure accurate conversion of circumference to diameter if required.

Measurement of the Circumference of the Pipe

In setting up the clamp-on ultrasonic flowmeter the pipe outside diameter is most commonly determined by measurement of the external circumference of the pipe.

Errors in measurement of the pipe circumference produce a bias in the volumetric flowrate measurement that is independent of flowrate. An overestimation of circumference causes an over-reading of flowrate and vice versa.

We find that for a given error the in measurement of the pipe circumference the error in flow measurement reduces with increasing pipe diameter and increases with increasing wall thickness. This is illustrated in the following Figure F.1 where errors of 1, 2 and 5 mm in measurement of the pipe circumference are converted into flowrate errors for pipes in the range of 25 to 2000 mm diameter with wall thickness of 5 or 10 mm. The graph shows that the resulting error is largely independent of the wall thickness for pipe diameters greater than 200 mm and that the magnitude of error is less than 1 % for pipes diameters greater than 300 mm. For smaller pipe sizes the errors could be relatively large.

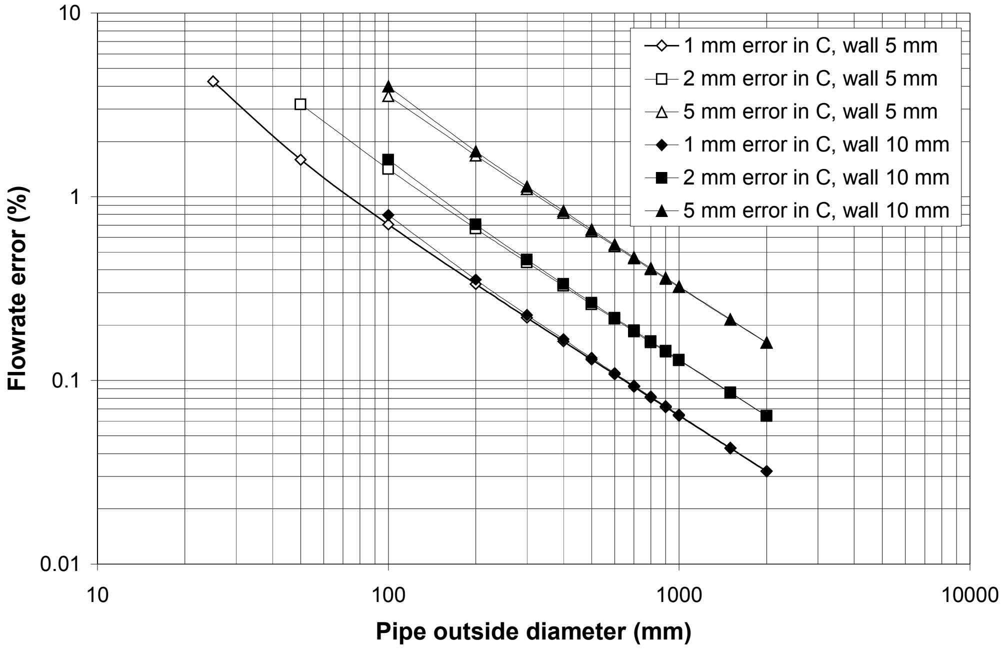


Figure F.1 Errors Resulting From the Measurement of Circumference

Measurement of the Wall and Liner Thickness

In setting up the clamp-on ultrasonic flowmeter the wall thickness is generally determined by measurement using an ultrasonic thickness gauge. Results obtained using these devices should be considered carefully as they could be prone to inaccuracy and they may only measure outer layer thickness of cement, rubber or epoxy lined metallic pipes.

As with the measurement of the pipe circumference it is important to realise that the uncertainty in volumetric flowrate is twice the fractional uncertainty in the internal pipe diameter.

Errors in determination of the total wall and liner thickness produce a bias in the volumetric flowrate measurement that is independent of flowrate. An overestimation of wall thickness causes an under-reading of flowrate and vice versa.

As in the case of measurement of the pipe circumference we find that for a given error in measurement of the wall thickness the error in flow measurement reduces in magnitude with increasing pipe diameter and increases in magnitude with increasing wall thickness. This is illustrated in the Figure F.2 where errors of 0.5, 1 and 2 mm in measurement of the wall thickness are converted into flowrate errors for pipes in the range of 25 to 2000 mm diameter with wall thickness of 5 or 10 mm. The graph shows that the resulting error is largely independent of the wall thickness for pipe diameters greater than 200 mm and that the magnitude of error is less than 1 % for pipes diameters greater than 300 mm. For smaller pipe sizes the errors can be relatively large.

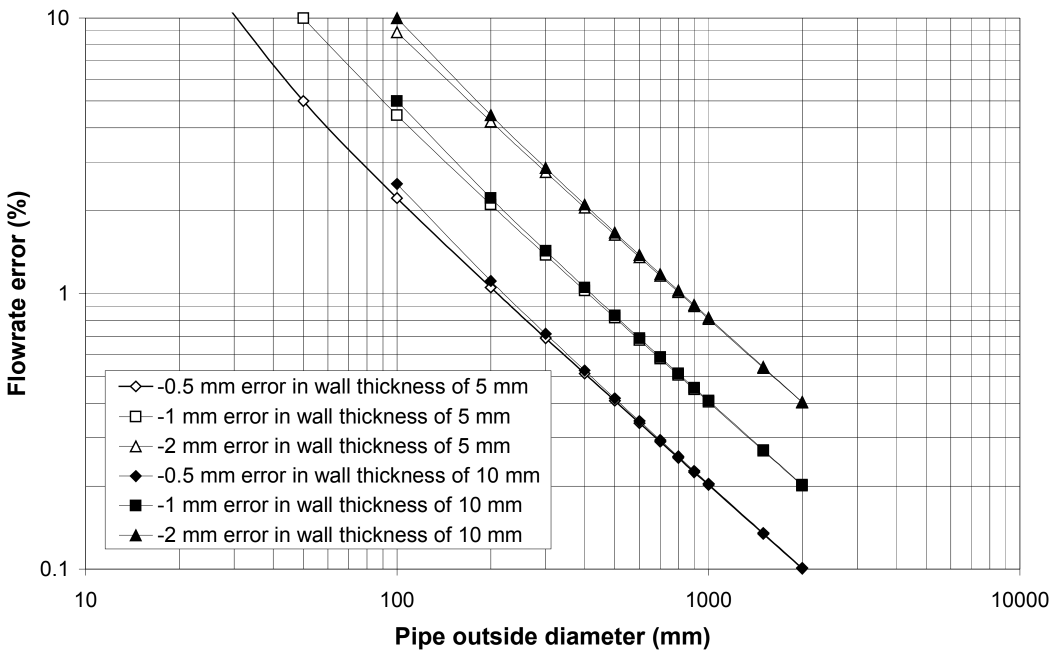


Figure F.2 Errors Resulting from Measurement of the Wall and Liner Thickness

Ovality

If a pipe has become distorted, for example due to force exerted on buried pipelines then the cross-section will change from circular to elliptical as illustrated in Figure F.3 below.

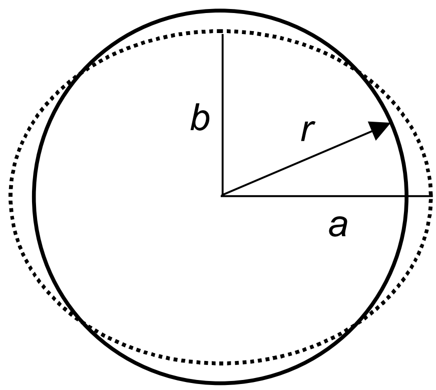


Figure F.3 Elliptical Distortion of a Pipe Section

If we assume that the pipe is round when in fact it is elliptical then the cross-sectional area of the pipe may be incorrect depending on how we have determined the pipe diameter. If the pipe circumference is measured and the diameter (and hence area) derived from this, then the errors will be relatively small and positive as plotted in Figure F.4 as a function of degree of eccentricity of the pipe (b/a). This calculated error does not account for the fact that the transit time measured by the meter may not correspond to the assumed diameter of the pipe. However, by placing the transducers at 45 degrees to the horizontal, the effect is negligible. This is recommended practice.

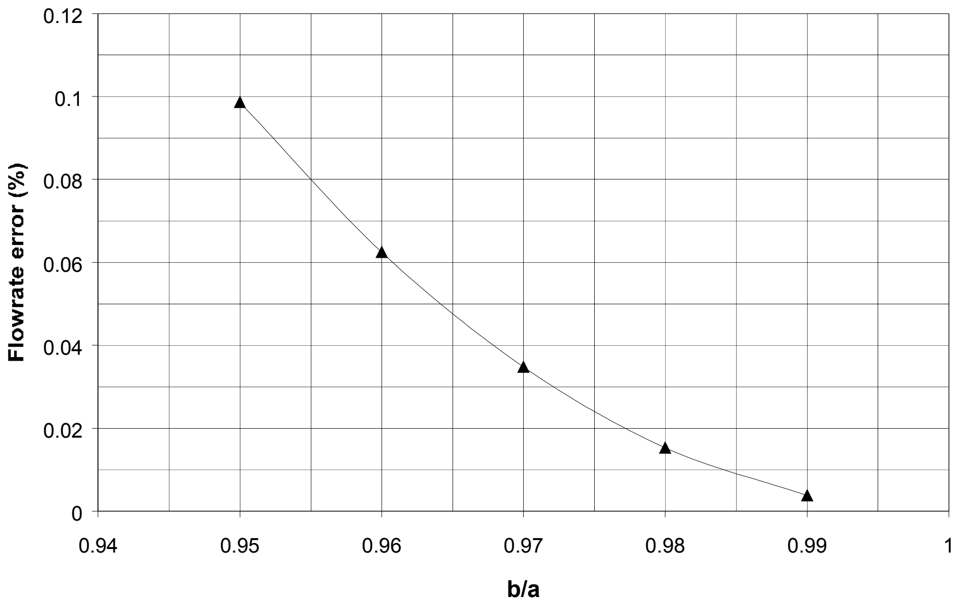


Figure F.4 Error Due to Ovality (for Measurement of the Apparent Circumference)

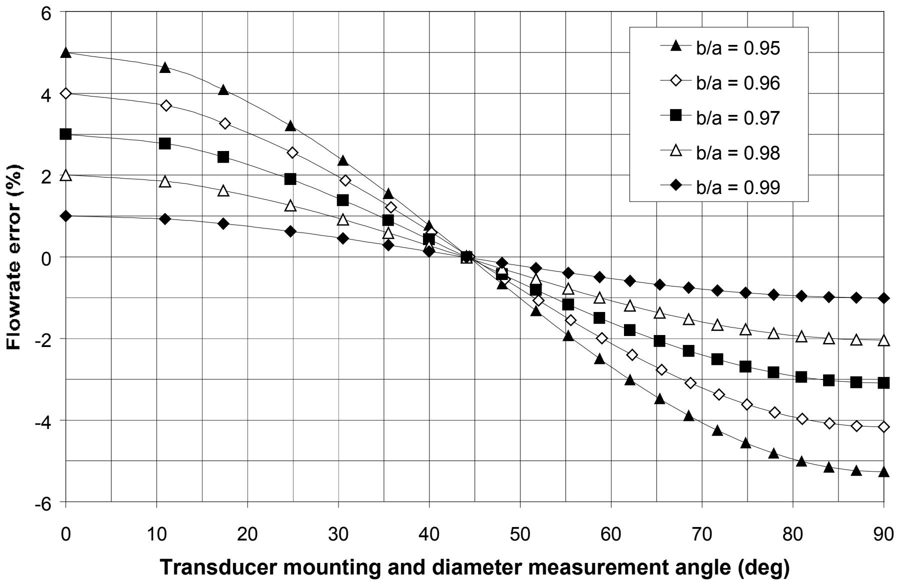


Figure F.5 Error Due to Ovality (for Measurement of the Apparent Diameter)

If however, we measure the diameter at a particular angle to the horizontal, passing through the centre of the pipe (as might be done using an insertion diameter gauging tool) then the resulting errors can be much more significant. Figure F.5 shows the error in flowrate due to measuring the traverse distance at various angles relative to the horizontal. As would be expected, measuring at the widest ‘diameter’ (i.e. zero degrees) produces an overestimation of the flowrate whereas measuring at the narrowest ‘diameter’ produces an underestimation of the flow of similar magnitude. The magnitude of error is dependent not the degree of eccentricity (b/a) in addition to the angle at which pipe diameter is measured as shown in Figure F.5. It is assumed in this example that the transducers are place on the same plane as the apparent diameter has been measured.

F.3.2 Determination of the Transducer Angle

It is shown in Appendix F1 that the angle of the transducer can be represented by two dimensions, *h* and *a* and that uncertainty in volumetric flowrate is equal to the fractional uncertainty in these dimensions. Assuming that *h* is constant, the exact placement of the transducer on the pipe wall, the application of the coupling material and the adjustment of the clamping mechanism will produce small changes in the '*a*' dimension. As this dimension is of the order of 20 mm a change of just 0.2 mm will result in an error of 1 % in flowrate. The sensitivity of the flowmeter to the transducer angle is independent of pipe size and flowrate.

This simple analysis is supported by experimental results. A clamp-on meter using two pairs of transducers was set-up on a six-inch pipe using clamps and straps to attach the transducers in a single reflection 'V' path. arrangement. To evaluate the sensitivity of the meter to the transducer placement, the meter was calibrated and then all of the transducers were removed with the mounting fixtures left in-situ. The locations of the transducer pairs were interchanged as were upstream or downstream transducers (whilst the pair matching was maintained). Using the parameters of the initial calibration curve fit to compare the indicated flowrate for velocities greater than 0.5 m/s, the mean error was 1 % and the variation about this mean was less than ±0.22% as shown in Figure F.6.

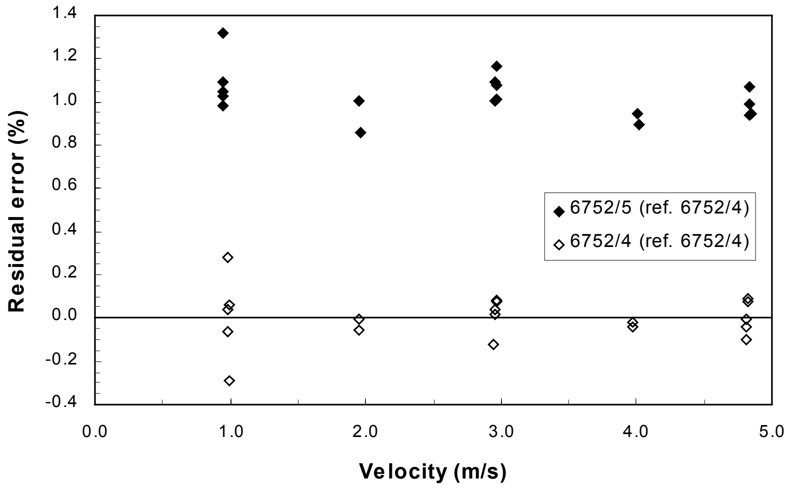


Figure F.6 Transducer Position Test Results

F.3.3 Transducer Temperature

The temperature of the transducer will affect the velocity of sound in the transducer material, c_t, and hence the calculated angle of the path in the flow. The magnitude of the resulting error is dependent on the properties of the transducer material. The transducer material will vary from manufacturer to manufacturer with a resulting influence on performance.

Tests at NEL have quantified the temperature effect for one particular clamp-on meter. The tests were conducted on a dual-path clamp-on meter by testing using two oils at different temperatures. The test involved a temperature change of 31 °C in the fluid whilst maintaining viscosity at a constant value for both calibrations. Ambient temperature was approximately 18 °C throughout. The results of this test are presented in Figure F.7, which shows a deviation of between 1 and 2 % between the two sets of data.

In practice in the water industry, water temperature and hence transducer temperature is unlikely to vary by more than 10 degrees C. The corresponding error would therefore be expected to be less than 1 %.

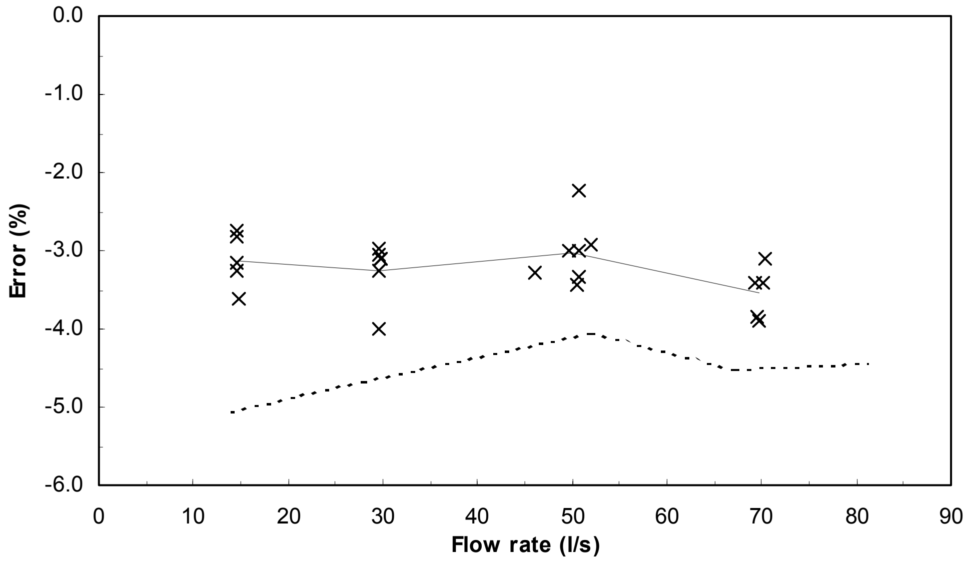


Figure F.7 Temperature Effect Test Result

F.3.4 Transit Time Difference Measurement

The relative uncertainty in Δt is dependent on the flow velocity. A simple estimate can be obtained by considering the timing clock resolution. Assuming a clock frequency of 100 MHz and ten thousand averaged measurements of the transit time difference interval we can ascribe an uncertainty of 0.05 nanoseconds for the timing resolution plus a zero-flow offset differential delay of 0.05 ns, giving a total figure of 0.1 ns. For clamp-on meters the signal-to-noise ratio is likely to be lower and poor alignment or coupling to the pipe wall may introduce a more significant differential delay so a figure of 0.5 nanoseconds could be applied. For pipe diameters of 100, 200, 400 and 1000 mm, this would result in the uncertainties shown in Figure F.8.

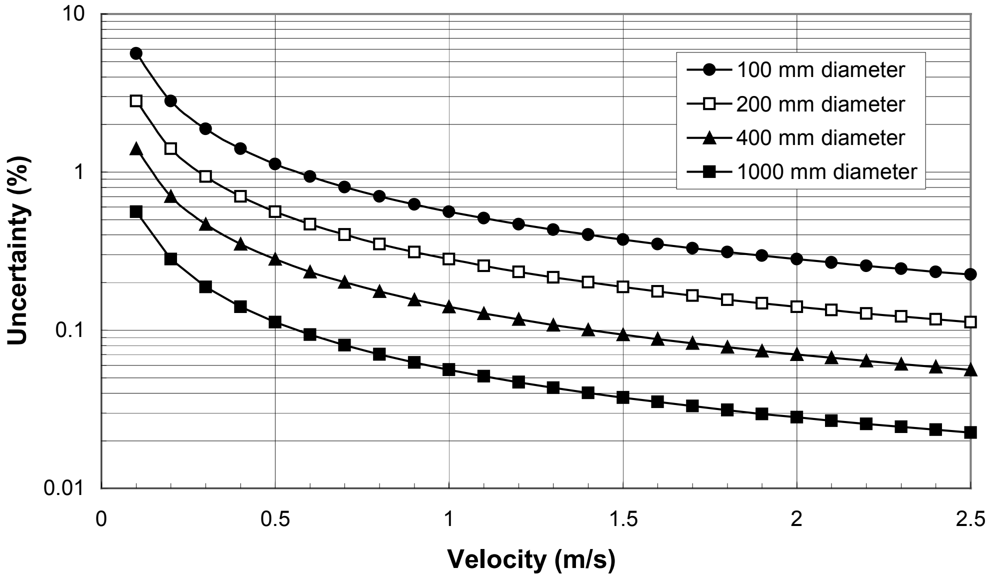


Figure F.8 Uncertainty Owing to the Transit Time Difference Measurement

The above treatment is an oversimplification although it does serve to illustrate the influence of pipe size and the error variation with flow velocity. In reality, flow turbulence means that above 1 or 2 m/s, the uncertainty owing to the transit time measurement does not reduce further. These characteristics have been observed in laboratory tests as illustrated in Figure F.9, which shows repeatability results for a clamp-on meter tested on 200 and 600 mm pipes (triangles and diamonds respectively).

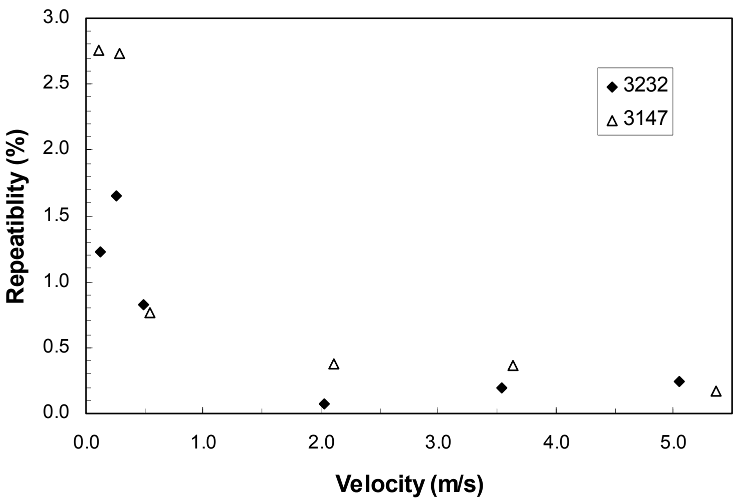


Figure F.9 Repeatability Characteristic Owing to Uncertainty in Δt

F.3.5 Transit Time Measurement

The uncertainty in measurement of the transit time t_f is dependent upon the delays in the electronics, transducers and pipe walls. If these are determined with reasonable accuracy we could assume a figure of significantly less than a microsecond for the uncertainty in t_f. However, poor estimates of pipe wall thickness, changes in fluid temperature and misplacement of transducers can lead to larger uncertainties in t_f. For example, a misplacement of a transducer by 10 mm could result in an additional time delay of the order of a microsecond.

Figure F.10 illustrates the potential magnitude of error for a practical range of errors in t_f.

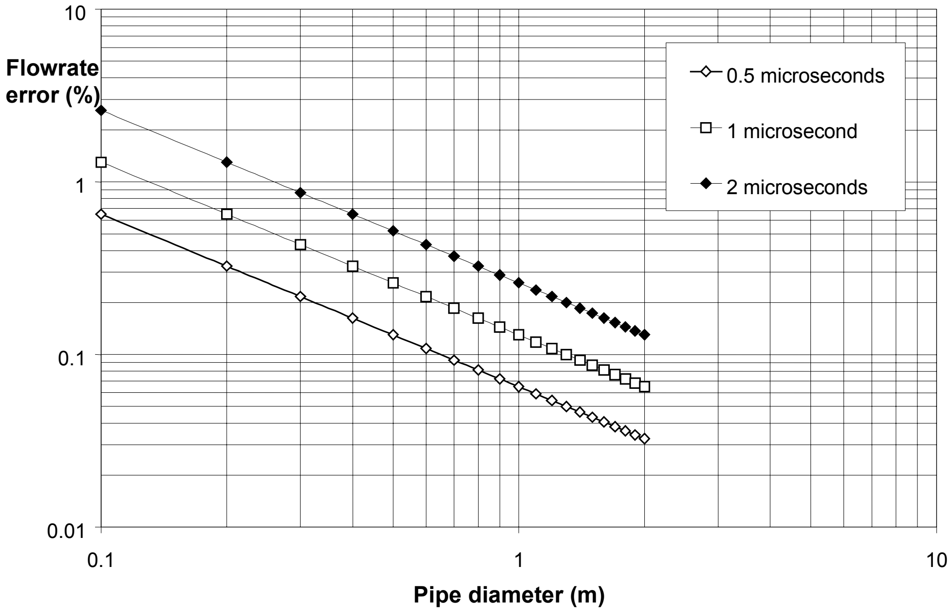


Figure F.10 Errors Resulting From Inaccurate Determination of the Transit Time

Such delays, however, are capable of being taken largely into account in the design of the meter. From discussions with one clamp-on ultrasonic manufacturer they indicated that although application dependent, the error once accounted for, would be in the region of 0.01 to 0.1% of flow reading.

F.3.6 Velocity Profile

A fully-developed flow profile is required for accurate measurement by a clamp-on ultrasonic meter. Clamp-on meters are particularly sensitive to flow profile as they only interrogate the flow on one or two diameters. So-called installation effects can easily be of the order of a few percent. Even with long straight lengths of pipe velocity profile effects can occur due to incorrect assumptions regarding pipe bore roughness or Reynolds number.

Pipe roughness is particularly important and clamp-on meters may take this into account by assuming a nominal roughness value in a profile correction factor. Figure F.11 below illustrates the effect of an increase in pipe roughness of 0.3 mm for two different pipe diameters.

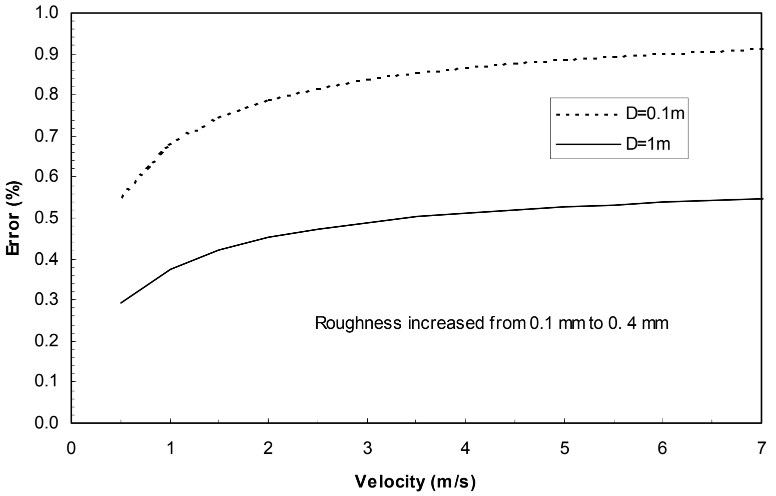


Figure F.11 Error Owing to Profile Change Due to Increased Pipe Roughness

The use of clamp-on transducers limits the potential accuracy of the transit time ultrasonic flowmeter because measurements are restricted to diametrical paths. The configurations in general use are particularly vulnerable to flow profile effects when used in single-path single-traverse configuration. This means that the velocity over the cross-section is sampled on only one chord and that this chordal measurement of velocity is prone to error when there are non-axial components of velocity (swirl) in the flow.

More paths generally improve performance relative to asymmetry but a limitation remains with the ability to make diameter measurements. To illustrate this point a velocity profile sensitivity analysis is presented which summarises the results from computational analysis of three path configurations and thirteen different two-dimensional velocity profiles. The three different configurations examined are shown in Figure F.12 and are described as follows:

A) A single diametric path
B) Dual diametric paths
C) Triple diametric paths

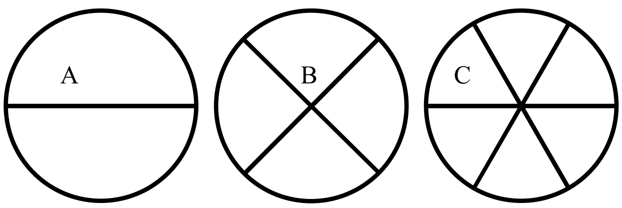


Figure F.12 The Path Configurations Used for 2D Modelling

The results shown in Figure F.13 have been derived by calculating the profile factor (v_{actual}/v_{meter}) for each configuration. By taking the average profile factor for each profile the errors relative to the average factor were calculated. Then, in order to produce a single value that could be used to evaluate the sensitivity of the configuration, the root of the mean of the squared errors (RMS error) was calculated. The methods applied are described in greater detail in the paper by

Brown, Barton and Moore [NEL/Norwegian Society of Oil and Gas Measurement, 'North Sea Flow Measurement Workshop', Oslo, Norway, October 1999].

The results in Figure F.13 demonstrate the high sensitivity of the single diameter to velocity profile. It can be seen that in most cases, introducing a second diameter reduces the sensitivity by a factor of 2 or more. However, the benefit of adding a third diameter does little to improve the measurement.

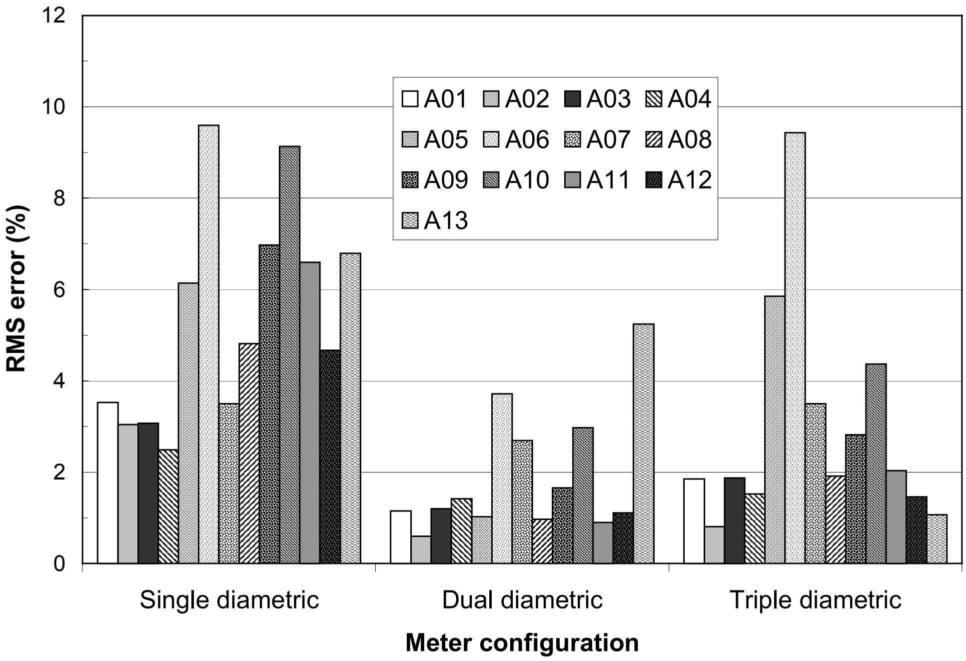


Figure F.13 A summary of Results From a Study Using Distorted Velocity Profiles

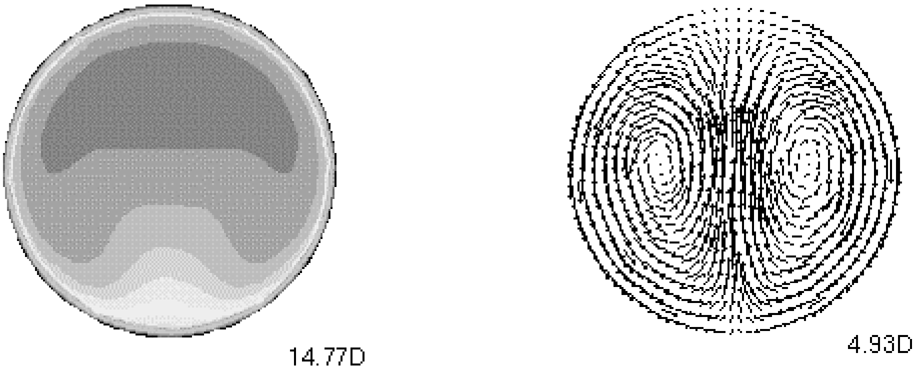
In practice it is necessary to have knowledge of how a particular meter set-up performs at various downstream distances from a range of profile-disturbing pipework components. In the past, NEL have tested clamp-on meters in a limited range of configurations and have applied computational fluid dynamics (CFD) to evaluate additional situations.

Here, we describe an experimental investigation at NEL into installation effects downstream of a single-bend. Both of the clamp-on meters were dual-path meters with their transducers mounted to form single-reflection paths in two perpendicular planes.

Figure F.14 shows characteristics of the flow downstream of a single bend as modelled using computational fluid dynamics (CFD). The plane of the bend is vertical with respect to Figure F.14. The momentum of the flow passing around the bend thrusts the fluid against the outside of the bend causing a high axial velocity at the 'top' of the pipe. The axial profile then distorts in quite a complex manner between about 5 and 12 diameters downstream. Beyond this region the profile reaches a relatively stable state in which high velocities occur at the top and around the sides of the pipe as shown in Figure F.14(a). Thirty diameters downstream the flow has not yet returned to a fully developed state.

A double vortex pattern is generated by the fluid motion as illustrated in Figure

F.14(b). Close to the bend the vortex pattern is clearly visible. After about 20D the vortices have practically disappeared demonstrating that downstream of a single bend, swirl decays at a greater rate than distortion of the axial velocity profile.



(a) (b)

Figure F.14 Flow Characteristics Downstream of the Single Bend

Experimental results were obtained at nominal downstream distances of 0, 10 and 20 diameters. In each case, the exact downstream distance was determined to allow comparison with the CFD results.

Figure F.15 shows the effect of the single bend on the results obtained both experimentally and using CFD. The results show negative shifts from the ideal calibration immediately downstream of the component reducing to be within 1 % about 15 diameters downstream. The figure shows good agreement between the experimental and simulated results with discrepancies typically less than 1 %.

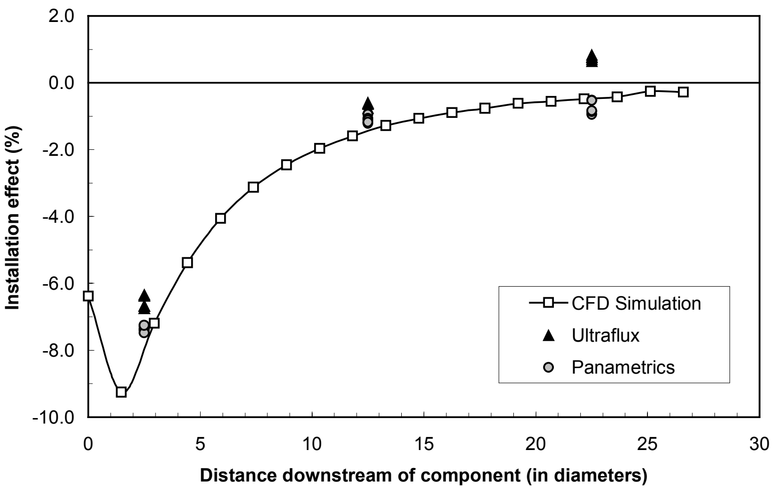


Figure F.15 Experimental and Simulated Errors Downstream of a Single Bend (Dual-Path, Double Traverse)

These results are for a dual-path double-traverse transducer configuration. In the case of a single-path single-traverse configuration, the magnitude of installation error could be much greater as illustrated by the CFD simulation result of Figure F.16.

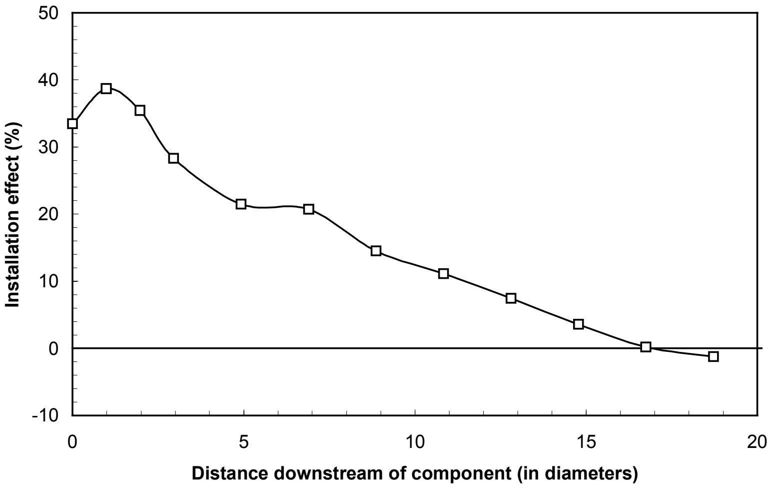


Figure F.16 The Installation Effects Downstream of a Single Bend (Single Path, Single Traverse)

F.4 DISCUSSION & GENERAL RECOMMENDATIONS

Even with sound knowledge of the set-up and installation conditions where a clamp-on meter is used, it may not be possible to evaluate the uncertainty with acceptable confidence. Where a verification result is in doubt it would be wise to repeat the verification exercise using a different location for the clamp-on meter to establish if the difference between clamp-on and permanent meter results is consistent.
The sight for the transducers should be chosen bearing in mind a number of concerns.

- Appropriateness for the flow which is to be verified – the meter should obviously be installed on the pipe of interest with no open branches between the flow that is to be verified and the clamp-on meter.

- Knowledge of pipe material and dimensions – pipe parameters are often entered in the form of outside diameter, wall thickness and liner thickness. Neglecting to enter liner values for a lined pipe will result in an over estimation of the flowrate, whereas entering liner values for a pipe which is unlined will result in an under estimation of the flowrate. Ultrasonic thickness gauges can be used to obtain a measure of pipewall thickness. These gauges cannot determine thickness beyond the first material interface and thus can only measure parent pipe wall thickness and not that of the pipe liner material. If possible a location should be chosen where the pipe is new and unlined and where accurate dimensional data is available.

- Proximity to bends, valves or other pipeline components – a long, straight pipe section should be used where possible. Disturbing components upstream of the transducers are much more important than those downstream. A rule of thumb that is easy to apply is that for any given length of straight pipe, $\frac{2}{3}$ to $\frac{3}{4}$ of the length should be upstream of the transducers.

- Pipe condition – if there is a variation in condition of the pipe along its length, generally a location that is most free of corrosion should be chosen. This should not take priority over the requirement for long straight lengths upstream unless it is not possible to obtain a good signal due to the pipe condition.

F.4.1 Transducer Set-up

The transducers should be spaced according to the meter manufacturer's set-up data. Care should be taken to ensure that any values used in the calculation of the transducer spacing (e.g. sound velocity or water temperature) are appropriate for the application. The suggested transducer spacing should be met as accurately as is practical (e.g. within one or two millimetres). In a single-reflection or V-configuration, accurate transducer spacing is more easily achieved.

Transducers are attached to the pipe by means of a magnetic clamp, or chain and strap arrangement or by using welded yokes. If the pipe is in fair condition then no treatment of the pipe surface is required. The area of the pipe where the transducers are applied can be treated prior to application to ensure a smooth finish free of debris or corrosion.

The transducers are applied to the pipe by tightening a screw on the transducer holder. A bead of couplant gel is applied to the transducer surface to form a thin layer between the active surface of the transducer and the pipe. This layer of couplant gel is used to ensure that the transmission of ultrasound into the pipe is efficient otherwise the majority of the ultrasound can be reflected back at the interface. For permanent applications, epoxy can be used and a number of solid elastomer materials are now available as a substitute to the gel couplant which can be vulnerable to washing or drying out. All couplants are proprietary and should be obtained from the meter manufacturer.

Care must be taken when using the gel couplant to ensure that neither too much nor too little is applied to the transducer face. Too little can result in a weak signal whereas too much can result in a noisy signal increasing the Δt uncertainty.

It is normal to mount a single pair of transducers on the same side of the pipe so that the sound travels in a reflected or ‘V’ path. When signal transmission is poor due to large pipe sizes or poor signal transmission through the pipe wall, ‘direct’ or ‘single-traverse’ paths can be used. On smaller pipes, to increase the ultrasonic path length, a triple-reflection or ‘W’ path can be used.

On a horizontal pipe it is advisable to avoid the top and bottom of the pipe due to the possibility of entrained gas or debris. This would normally mean avoiding the 11 to 1 o’clock and 5 to 7 o’clock positions round the circumference of the pipe. If two pairs of transducers are used the same rules apply and it is normal to orient the two paths in planes which are at 90 degrees to one another (e.g. with transducers at the hour-hand positions for 1.30 and 4.30).

It is good practice to avoid the use of clamp-on ultrasonic meters on downward flowing vertical pipes. Not only does this introduce uncertainties in the flow profile but there is a strong possibility of a loss of signal due to the non-wetting of the pipewall interior by the fluid. If the process pump does not maintain sufficient back pressure, for example, there is also the potential for errors due to the effect of gravity on the fluid.

It is also good practice to avoid mounting a transducer on the pipe where the surface is uneven or where there may be internal defects (e.g. weld lines). Care should also be taken to avoid reflecting the ultrasound on an internal area which may be uneven (e.g. a horizontal pipe seam).

As transducers are not specific to the unit, other transducers supplied by the manufacturer can be used. However, each transducer has been matched to another by the manufacture and care should be taken to avoid mismatching transducer pairs.

F.4.2 In-situ Performance

Laboratory and field trial results generally suggest that with sufficient care and a good location of the transducers, it is possible to set up a clamp-on meter so that the uncertainty is in the region of 2 to 5 percent.

In some situations it may not be possible to make a measurement due to excessive signal attenuation, perhaps due to a separated pipe liner or severe scaling inside the pipe.

Laboratory tests on an 8-inch cement lined ductile iron pipe suggest that some types of pipe material and/or liner could be more problematic than unlined steel or plastic pipes.

Where the readings from a clamp-on meter are in doubt, either because installation and set-up conditions are poor or because of disagreement with a permanently installed meter, it is wise to repeat the verification exercise. When this is done a different location should be selected for the transducers and the path orientation relative to the clock-face should be changed. This should cause pipewall or fluid velocity profile effects to vary, which will be picked up in the verification results.

F.4.3 Long-term Performance

Ultrasonic meters should be stable in the long term if three conditions are met:

- The condition of the transducers and their coupling to the pipe is not significantly altered.
- The condition of the pipe is not significantly altered.
- The fluid and flow behaviour does not change significantly.

It can be shown that unclamping and re-clamping of transducers can result in a difference of the order of one percent. Therefore, in situations where repeated verifications are carried out on the same pipe, it is advisable to use welded yokes to hold the transducers and, if possible use a dedicated pair of transducers with solid couplant so that they can be left in-situ undisturbed. Where a site is going to be used for clamp-on meters it is advisable to protect the transducer site from the outside environment.

If the fluid properties change then it is possible that errors will result. For example, if a change in water temperature causes the velocity of sound in the water to increase then the change in the angle of refraction may cause the ultrasonic beam to begin to miss the receiving transducer.

F.4.4 Diagnostic Checks

Modern ultrasonic meters have the capability to report parameters that can be used to verify the health of the meter and its interaction with the flow.

These diagnostic parameters differ from meter to meter and the user is dependent on the information provided by the manufacture regarding what are acceptable limits for these parameters. It is important to realise that these parameters have not been directly correlated with performance in terms of flow measurement error and that at present the best they can offer is the sign of a good signal or a poor signal, they cannot indicate accuracy.

Use of a comparison of the reported sound speed against tabulated values is useful for diagnostic purposes. A discrepancy in sound speed will indicate an error in the pipe dimensional data or the transit time measurement. For water at around 20 degrees Celsius a discrepancy in sound speed of 15 m/s corresponds to approximately 1% error and a discrepancy of 80 m/s corresponds to approximately 5% error. Discrepancies of this magnitude could indicate, for example, the presence of a pipe liner that had been overlooked when setting up the meter.

F.4.5 Data Recording

Given the importance of proper set-up of the meter and the need for proper knowledge of the conditions, under which verification has been carried out, it is recommended that comprehensive data recording be carried out. This involves the recording of details about the site, including dimensional characteristics of the pipe on which the meter is to be installed and also the recording of set-up parameters, diagnostics parameters and relevant observations. This can be performed effectively using laptop PC technology for which some manufacturers have developed flowmeter interface software. It is also recommended that full use is made of standard pipe tables or the manufacturer's data for the pipe in question. These data can then be used to verify/confirm the measurements made on site and thus reduces the potential for human error.

For the site set up, a generic approach can be taken. However, for every ultrasonic meter manufacturer, the set-up and diagnostic details will vary slightly. It is recommended that methods of recording data be customised to individual company needs and practices. Sample datasheets are included in Appendix F2 as an example of the appropriate level of detailed information that should be recorded. The particulars of the one specific clamp-on flowmeter have been used in the example.

F.5 CONCLUSIONS

Knowledge of, and proper use of, the pipe material and dimensional information is very important. The resulting uncertainty in volumetric flowrate is twice the fractional uncertainty in the internal pipe diameter. Pipe and liner material and thickness must also be known.

Care must be taken in attaching the transducers to the pipe as poor control of the clamping process will affect the overall uncertainty.

Transit time and transit time difference measurements can be made accurately but can be prone to additional errors that are generally difficult to quantify.

Velocity profile has a very large part to play in the uncertainty of measurement when using clamp-on ultrasonic meters. In many instances it is likely that velocity profile will be the single largest contributor to uncertainty in measurement.

Each of the different sources of uncertainty can contribute significantly to the overall uncertainty. Determination of an appropriate input value for each source of uncertainty requires evaluation of the conditions under which the particular measurements were made. Depending on the precise method used to evaluate the overall uncertainty, for example straight addition or root-sum-square techniques, the result can be biased somewhat to be pessimistic or optimistic. By whichever method is employed, the combined uncertainty is likely to be in excess of 2% and could easily be significantly larger.

To achieve a low uncertainty, in the region of 2 – 5%, the key conditions that should be met are as follows:

- The pipe should be in good condition externally and internally
- The site were the transducers are installed should ensure the avoidance of welds and joints and should be situated well downstream (e.g. no less than 20 straight diameters) of any disturbing pipe components such as bends or valves
- The pipe dimensional details should be know with low uncertainty, including liner details
- The ultrasonic equipment should be known to be in good working order
- The installation of the transducers and set-up of the parameters in the electronic hardware should be performed by a competent operator

APPENDIX F1 –

THEORY

Nomenclature

Symbol	*Description*
D	Pipe internal diameter
k_p	Flow profile correction factor
c_f	Fluid sonic velocity
Δt	Measured transit time differential
C	Measured external circumference of pipe
v	Estimated velocity
θ	Angle of wave propagation (path) in fluid
c_t	Wave velocity in transducer
α	Angle of wave propagation in transducer
β	Angle of wave propagation in pipe wall
c_p	Wave velocity in pipe wall
w	Measured pipe wall thickness
t_m	Measured transit time through fluid and pipe walls
t_f	Transit time through fluid

The measurement principle is based on the determination of the propagation time of ultrasound in the flowing fluid. Generally, the assertion that the apparent velocity along a ray is given by the velocity of sound in the fluid at rest, c_f, plus the component of fluid velocity along the ray is applied. To eliminate the velocity of sound from the subsequent derivation, transit times are determined both in the direction of flow and against it. Considering the general ray geometry shown below the upstream transit time and downstream transit times are given by

$$t_{ab} = \frac{L}{(c_f + v\cos\theta)} \quad \text{and} \quad t_{ba} = \frac{L}{(c_f - v\cos\theta)} \qquad \text{(F1.1)}$$

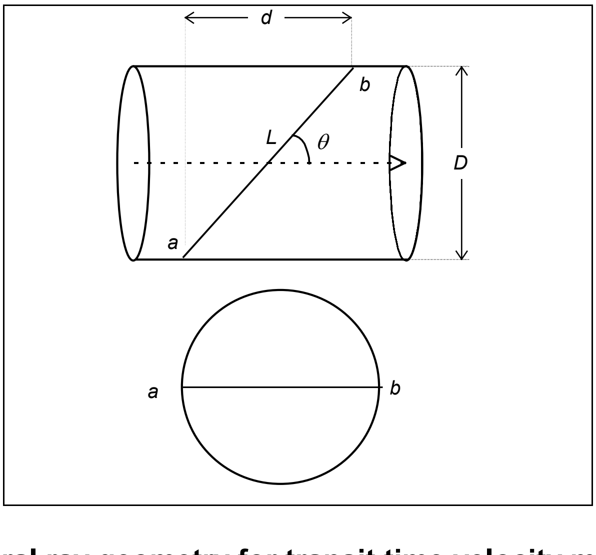


Figure F1.1 - General ray geometry for transit time velocity measurement

There are four basic methods by which transit time velocity measurement is performed; direct time differential, phase differential, phase control, and frequency differential. In one manufacturer's flowmeters the direct time differential method is applied. Short pulses are propagated upstream and downstream and the time interval for each excitation/detection is measured against an accurate high-frequency clock using digital signal processing techniques. The velocity is determined from the reciprocal of the transit times as follows:

$$\frac{1}{t_{ab}} - \frac{1}{t_{ba}} = \frac{(c_f + v\cos\theta) - (c_f - v\cos\theta)}{L} \tag{F1.2}$$

$$v = \frac{L}{2\cos\theta}\frac{\Delta t}{t_{ab}t_{ba}} \tag{F1.3}$$

Multiplying the velocity by the cross-sectional area of the flow, *A*, the volumetric flowrate is obtained.

$$q_v = A\frac{L}{2\cos\theta}\frac{\Delta t}{t_{ab}t_{ba}} \tag{F1.4}$$

This equation can now be further simplified as t_{ab} and t_{ba} are much larger than Δt, permitting the substitution of each with t_f to give

$$q_v = A\frac{L}{2\cos\theta}\frac{\Delta t}{t_f^{\,2}} \tag{F1.5}$$

For clamp-on meters, each measurement path is a single or multiple diameter traverse. Therefore, the *L* dimension is a function of the diameter and path angle.

$$L = \frac{D}{\sin\theta} \tag{F1.6}$$

The *L* dimension can also be calculated as a function of the measured transit time and the velocity of sound in the fluid.

$$L = c_f t_f \tag{F1.7}$$

The path angle is dependent on the velocity of sound in the fluid and is governed by Snell's law which can be presented as

$$\frac{\cos\theta}{c_f} = \frac{\cos\beta}{c_p} = \frac{\cos\alpha}{c_t} \tag{F1.8}$$

This can be rearranged to give the velocity of sound in the fluid as a function of the wave angle in the transducer, the wave velocity in the transducer and the path angle in the fluid.

$$c_f = \frac{c_t \cos\theta}{\cos\alpha} \tag{F1.9}$$

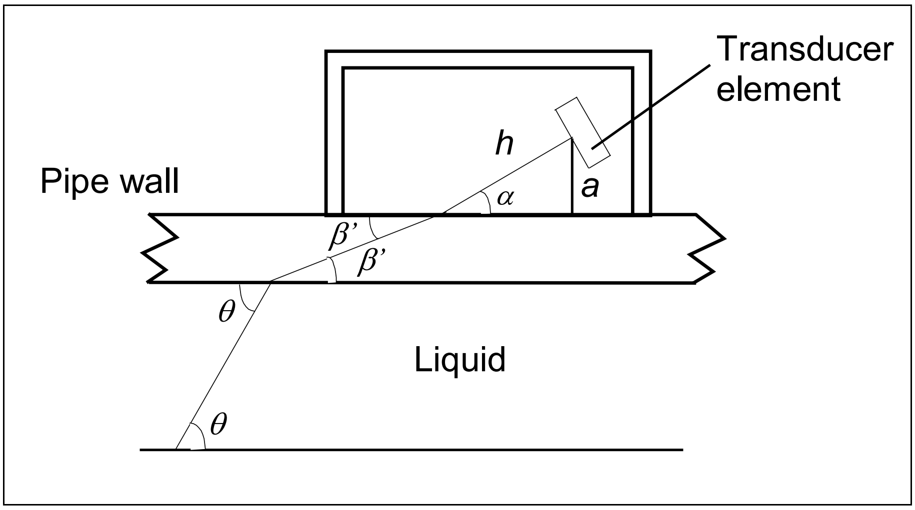


Figure F1.2 – Wave angles determined by Snell's Law

Substituting equation F1.9 into equation F1.7 gives the result

$$L = \frac{c_t t_f \cos\theta}{\cos\alpha} \tag{F1.10}$$

The area can also be substituted as a function of *D*.

$$A = \frac{\pi D^2}{4} \tag{F1.11}$$

Substituting equations F1.10 and F1.11 into equation F1.5 we obtain the result

$$q_v = \frac{\pi D^2}{8} \frac{c_t}{\cos\alpha} \frac{\Delta t}{t_f} \tag{F1.12}$$

To simplify the above equation further for analysis, we can define the angle in the transducer in terms of the two dimensions shown in Figure F1.2.

$$\cos\alpha = \frac{a}{h} \tag{F1.13}$$

Substituting equation F1.13 into equation F1.12 we obtain the result

$$q_v = \frac{\pi D^2}{8} \frac{c_t h}{a} \frac{\Delta t}{t_f} \tag{F1.14}$$

Given in the form above, the effects of non-uniform distribution and non-axial components of velocity in the cross-section on the estimation of the mean velocity are neglected. As the velocity is measured on one or two paths and this is used to estimate the mean velocity in the pipe cross-section, it is necessary to introduce a 'profile correction factor', k_p.

$$q_v = k_p \frac{\pi D^2}{8} \frac{c_t h}{a} \frac{\Delta t}{t_f} \qquad \text{(F1.15)}$$

The expected performance can now be quantified by determining the sensitivity coefficients of equation F1.15 by partial differentiation and estimating the uncertainties in each of the parameters.

Table F1.1 – The Relative Sensitivity Coefficients of Equation F1.15

$\frac{\partial q_v}{\partial k_p}\frac{k_p}{q_v}$	$\frac{\partial q_v}{\partial D}\frac{D}{q_v}$	$\frac{\partial q_v}{\partial c_t}\frac{c_t}{q_v}$	$\frac{\partial q_v}{\partial h}\frac{h}{q_v}$	$\frac{\partial q_v}{\partial \Delta t}\frac{\Delta t}{q_v}$	$\frac{\partial q_v}{\partial a}\frac{a}{q_v}$	$\frac{\partial q_v}{\partial t_f}\frac{t_f}{q_v}$
1	2	1	1	1	-1	-1

It follows that, for example, a one percent error in pipe bore will result in an two percent error in q_v. Such considerations are especially important in relation to clamp-on ultrasonic meters as the dimensions of the conduit may not be known with great certainty.

The above also illustrates that the sensitivity of equation 15 to changes in Δt is constant and therefore, as velocity decreases and the transit time difference measurement tends towards zero, uncertainty in the flowrate measurement increases.

If we assume circularity then the pipe internal diameter is simply given by

$$D = \frac{C}{\pi} - 2w\,. \qquad \text{(F1.16)}$$

APPENDIX F2 –

EXAMPLE RECORD SHEETS

SITE REFERENCE DATA

Area:
Zone:
Site reference:
Verification site ID:

PIPE DETAILS

Pipe material:	Pipe wall thickness:
Pipe outside diameter (OD):	Liner material:
Pipe inside diameter (ID):	Lining thickness:

Provide details of how above measurements were obtained
e.g. Measuring tape applied to circumference
Caliper measurements on outside diameter
Insertion gauge used to measure inside diameter
Pipe wall thickness by ultrasonic gauge

Assessment of general condition of pipe:
e.g. New/Good/Reasonable/Poor

Assumed internal roughness:

Pipe configuration details relative to transducer location
Drawing reference:
Drawing storage location:

Observations
e.g. Distance to nearest upstream fitting:
Type of upstream fitting:
Distance to nearest downstream fitting:
Type of downstream fitting:
Distance to reductions or expansions:
Other:

CLAMP-ON VERIFICATION RECORD DATA

Date and time:

Area:

Zone:

Site reference:

Verification site ID (and flowmeter 'site' name):

FLOWMETER SETUP

Transducer type:
Serial numbers:

PIPE DETAILS - Refer to corresponding site reference data sheet

Pipe material:	Liner material:
Pipe outside diameter (OD):	Lining thickness:
Pipe wall thickness:	

Fluid type:

Fluid temperature:
Means of obtaining fluid temperature

Reynolds number correction settings:	
e.g.	Assumed viscosity:
	Viscosity from VOS

Channel set up

	Channel 1	Channel 2
AVERAGING		
Response time		
SIGNAL		
Signal low limit		
Corr. peak limit		
Sound speed +/-		
Velocity low limit		
Velocity high limit		
Acceleration limit		
Amp. discrim. low		
Amp. discrim. high		
Delta T offset		
% of peak		
Transmitter voltage		
Transmit sample		

CLAMP-ON DIAGNOSTIC DATA
Note: It is good practice to record diagnostic data in an electronic log file rather than manually
The log file should be set up to record at intervals of a few seconds over several minutes

Date and time:

Area:

Zone:

Site reference:

Verification site ID (and flowmeter 'site' name):

PIPE DETAILS - See corresponding site reference data sheet

SET-UP DATA - See corresponding verification record data sheet

Panametrics Diagnostics

Logfile name:

	Channel 1	Channel 2
Velocity		
Vol. flow rate		
Signal strength up		
Signal strength down		
Sound speed		
T up		
T down		
Delta T		
Reynolds number		
K(Re)		
Peak(%)		
Theta		
Q up		
Q down		
Amp up		
Amp down		
P# up		
P# down		
NF up		
NF down		
Cxdcr		

Sound speed from tabulated data:

Difference between observed and tabulated sound speed in m/s and %:

APPENDIX G

CASE STUDY REPORT:
THE ERRORS IN THE DATA PATH FROM METER THROUGH TELEMETRY

EXECUTIVE SUMMARY – APPENDIX G

The drive for improved flowmetering accuracy from regulatory bodies such as the Environment Agency and OFWAT has particularly concentrated on improving the performance of primary flowmetering devices. This report presents the findings from an investigation into the errors that can be introduced once a flow measurement signal has been generated and follows the signal path from the meter, through telemetry, to the data that is viewed by the users on their computers in the office.

Three site visits were carried out to 3 separate reservoirs, (sites 1 to 3), and in all three instances artificial flow signals were generated at the flowmeters by using a 4 to 20 mA current source simulator to test the signal path.

From the tests performed at the inlet electromagnetic meter at site 1, the worst error between the RTS screen and the Magmaster transmitter output was calculated to be 0.64%. At this site it was found that the resistor used to convert the mA signal to a voltage was not of the wire wound precision type. Instead, a ceramic resistor with a tolerance of ± 0.5% had been installed and the resulting maximum voltage error of 0.4% is consistent with this finding. If a higher precision resistor was installed instead this error would reduce to below 0.1%. From an assessment of the clamp-on ultrasonic meter at site 1 it is concluded that care has to be taken when including additional components into the signal loop such as an LCD. It is calculated that if such a component were to be added to the present system then an error of 2.4% would be introduced (at maximum flowrate).

Errors were also calculated at the electromagnetic outlet meter at the second site. This site introduced extra uncertainties due to the radio link between the meter and the receiver at the outstation. The 250 ohm resistor used at this site to convert the 4-20 mA signal into a corresponding voltage is this time of the higher precision wire wound type. The resulting signal errors in the voltage conversion were now shown to be less than 0.1%, consistent with the performance rating of the resistor. A comparison of the signals received at the outstation with the signals on RTS indicated that errors of around 1% can be produced.

Lastly, signal checks were also carried out on an inlet electromagnetic flowmeter at the site 3 reservoir. The largest discrepancy between expected and recorded signals was found to be 0.50% and represents the difference between the telemetry outstation and RTS displays. One reason suggested for this difference is the signal isolator in the flow controller which may possibly be out of linearity. The largest error in the digital signal measurements was 0.25%. At this site, the precision resistor was measured to be 250.178 ohms and is within the specified tolerance of ± 0.1% ohms. The flow signal was also traced through the SCADA system. Here, it was found that the SCADA signal had indicated no error at all. The reason for this is considered to be due to the resolution of the display and in this case the errors have been rounded down to zero. It should therefore be borne in mind that an exercise like this might indicate larger errors than expected if the errors happened to be rounded upwards.

It is concluded that errors are introduced into the signal in the data path from meter through to telemetry. Although the errors at the three sites investigated may appear to be reasonably small, it is still considered important that procedures such as those carried out should be performed. This will allow any problems in the data path to be highlighted at an early stage and will help ensure that the flow data is reliable.

C O N T E N T S

G.1 INTRODUCTION

Regulatory bodies in the UK such as the Environment Agency and OFWAT have demanded that the water companies rise to the challenge of improving their flow measurement. In general, the water companies have been steadily improving their flow measurement systems and procedures to meet this challenge and it is now common for them to have in place various systems for verifying the performance of their flowmetering devices. These include the use of secondary metering devices such as clamp-on ultrasonics and insertion probes as well as the application of meter manufacturer's diagnostic verification tools. The main focus during such verifications is to check the performance of the flow measurement device. It is recognised, however, that the electronic flow signal being generated by the meter (typically mA) is still required to be converted into meaningful flowrate information (tcmd). The work presented here reports on the measurements made during a number of site visits to a water company and identifies and quantifies the errors that can be introduced into the data path once the flow signal has been generated.

Three site visits were carried out to 3 separate reservoirs, (sites 1 to 3), and in all three instances artificial flow signals were generated in the flowmeters by using a 4 to 20 mA current source simulator.

It is common for a flowmeter’s range to be set up such that a 4 mA signal is generated at zero flow and a 20 mA generated at full scale. It is stressed, however, that during these exercises it was never the intention to evaluate the accuracy of the primary device output signal (mA) with the actual volumetric water flow. Instead, the focus was on the other sources of error which can contribute to the overall uncertainty in the signal path. This case study therefore aims to identify and quantify the errors that can be introduced once the flow signal has been generated.

Since the flow through these flowmeters is demand dependent, there is a continuously varying output signal generated by the primary device (flow sensor) which is then amplified and processed by the secondary device. This complicates the ability to be able to compare the meter output signal with the signal at other points in the signal path. This problem is overcome by using a current source simulator whereby the input to the secondary device from the primary device is bypassed and a simulated signal is used instead. Since this signal can be maintained at a constant value, this allows a comparison to be made on a like-with-like basis throughout the signal path.

The funding for this research was provided by the UK’s Department of Trade and Industry through the NMSPU (National Measurement System Policy Unit) 1999-2002 Flow Programme, together with co-funding from a number of water companies: Anglian Water, Dwr Cymru, Northumbrian Water, Southern Water, Thames Water and Yorkshire Water. The major advantage to be gained from this collaboration with the water companies is the direction and support they have provided, ensuring that the research is carried out with a focus on issues of particular industrial relevance. A major part of this project was to undertake a number of case studies and this report presents the findings from one such study carried out for one of the water companies.

During the three site visits, a number of different metering systems were investigated:

G.2 ERRORS IN THE INLET ELECTROMAGNETIC METER AT SITE 1

A schematic showing the ABB *Magmaster* loop check that was conducted on the inlet meter is shown in Figure G.1. The following gives a brief running commentary of the procedures that were performed and the resulting errors in data transmission which were obtained.

G.2.1 Range and Zero Flow Errors With and Without Magmaster Display Connected

The range setting of the Magmaster electromagnetic flowmeter had been set such that at zero flow the current output should generate 4 mA. Similarly, the full range flow of 25 thousand cubic meters per day (tcmd) should be indicated by a current of 20 mA. The first exercise was to apply the (calibrated) current source simulator (Fluke meter) on the Magmaster transmitter for 3 values of flowrate: (1) no flow, (2) half flow (= 12.5 tcmd) and (3) full flow = (25 tcmd) and measure the current required to generate those outputs. The resulting outputs measured with the transmitter display still connected was 4.00, 11.98 and 19.97 mA respectively. Similarly, the outputs with the transmitter display disconnected gave results of 4.00, 11.98 and 19.96 mA. These results were then compared to the ‘ideal’ outputs of 4.00 mA (zero flow), 12 mA (half flow) and 20 mA (full flow) and the corresponding errors calculated. Table G.1 summarises this information together with the resulting errors.

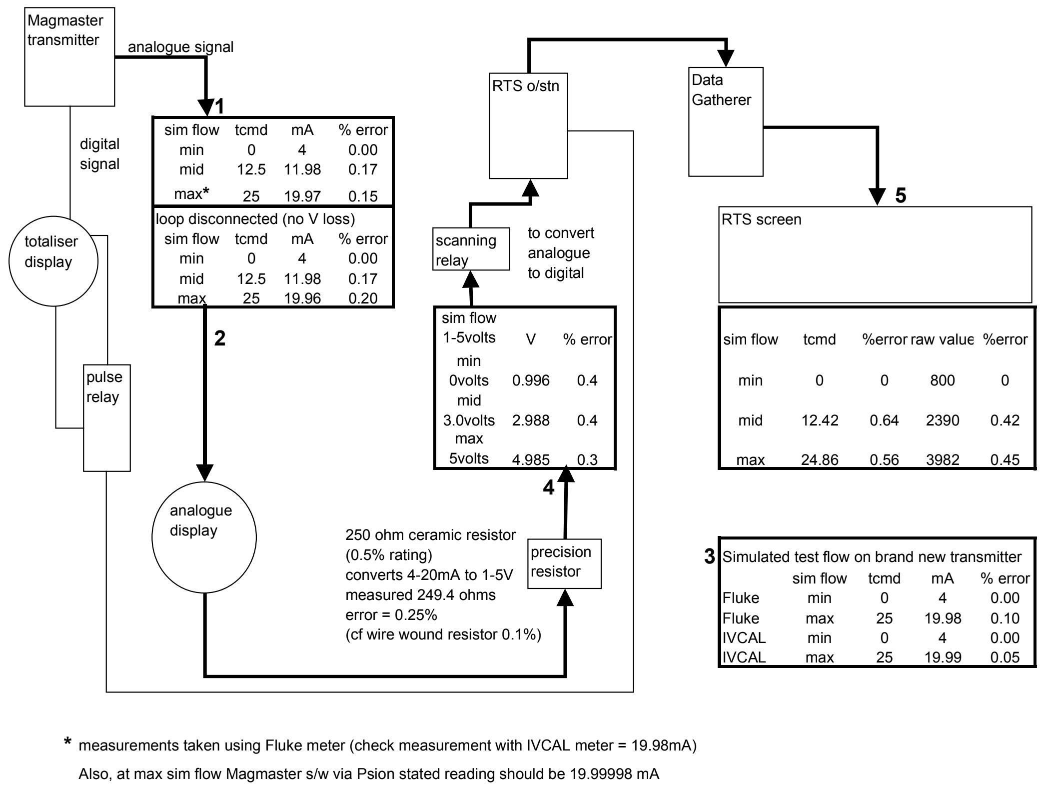


Figure G.1 Magmaster Loop Check on Inlet Meter at Site 1 Reservoir

Table G.1 Comparison of Transmitter Errors at Varying Simulated Flowrates

Simulated Flow	Flow (tcmd)	Ideal mA	ACTUAL Loop Connected mA	ACTUAL Loop Connected % Error	ACTUAL Loop Disconnected mA	ACTUAL Loop Disconnected % Error
Zero Flow	0	4	4.00	0.00	4.00	0.00
Half Flow	12.5	12	11.98	-0.17	11.98	-0.17
Full Flow	25	20	19.97	-0.15	19.96	-0.20

G.2.2 Comparison With Brand New Magmaster Transmitter

As part of the evaluation being carried out on the inlet meter a brand new Magmaster transmitter was available. This time the simulated currents were measured for the zero output and full scale (25 tcmd) settings. Firstly, these measurements were made with a Fluke meter (as before) and secondly with an IVCAL meter. A summary of the results from this checking procedure are detailed in Table G.2.

Table G.2 Simulated Test Flow on Brand New Magmaster Transmitter

Check Meter Instrumentation	Simulated Flow	Flow (tcmd)	Ideal mA	ACTUAL mA	ACTUAL % Error
Fluke	Zero Flow	0	4	4.00	0.00
Fluke	Full Flow	25	20	19.98	-0.10
IVCAL	Zero Flow	0	4	4.00	0.00
IVCAL	Full Flow	25	20	19.99	-0.05

G.2.3 Voltage Errors

The analogue current output from the transmitter (4 to 20 mA) is passed through a precision resistor and the resulting potential difference (1 to 5 V) is used by the scanning relay to convert this analogue signal into a digital output. Table G.3 summarises the voltages that were measured for the zero, half and full flow conditions together with the resulting errors.

It is noted, despite the requirement for a high precision resistor in the above circuitry, that the resistor in place at the time of these tests was a lower precision ceramic type with a quoted uncertainty of 250 ohms ± 0.5%. This compares to the higher precision wire wound resistor type with a rating of 250 ± 0.1% which really ought to have been in place.

Table G.3 Voltage Conversion Errors

Simulated Flow	Flow (tcmd)	Ideal V	ACTUAL V	ACTUAL % Error
Zero Flow	0	1	0.996	-0.4
Half Flow	12.5	3	2.988	-0.4
Full Flow	25	5	4.985	-0.3

G.2.4 Comparison of Simulated Flows With RTS Output

The last stage in the assessment of the simulated flow signal through telemetry is to examine the values recorded on the RTS (Regional Telemetry System) display. Here, both the volumetric flow (tcmd) and the digital signal (bits) for each flow rate are recorded. Table G.4 summarises the figures obtained together with the resulting errors. The RTS is widely available to personnel throughout the water company and the users gain access to it from their personnel computers or workstations in their offices.

Table G. 4 RTS (Regional Telemetry System) Outstation Errors

Simulated Flow	Ideal Flow (tcmd)	Measured Flow (tcmd)	% Error	Ideal Count (Bits)	Measured Count (Bits)	% Error
Zero Flow	0	0	0.00	800	800	0.00
Half Flow	12.5	12.42	-0.64	2,400	2,390	-0.42
Full Flow	25	24.86	-0.56	4,000	3,982	-0.45

G.2.5 Conclusions

Overall, it has been shown that errors are introduced in the signal loop due to the introduction of various electronic components. The worst error in the exercise performed above was with the simulated ‘half flow’ whereby there was a measured discrepancy between the RTS screen and the Magmaster transmitter output of 0.64%.

The errors introduced by the instrumentation described in Sections G.2.1 and G.2.2 are within the manufacturer's rated uncertainty specification of ± 0.25%. As described in Section G.2.3 (Table G.3), the 250 ohm resistor introduced an error of around 0.4%. This is again within the specification of the ceramic resistor whereby the manufacturer's quote an uncertainty of ± 0.5%. There are therefore clear benefits, as discussed in Section G.2.3, of fitting a high precision wire wound resistor with an uncertainty of ± 0.1% in place of this ceramic type.

Lastly, the errors recorded in Section G.2.4 represent the cumulative errors introduced in the system up to the point of conversion from analogue to digital.

G.3 ERRORS IN OUTLET ULTRASONIC CLAMP-ON METER AT SITE 1

A schematic showing the clamp-on ultrasonic loop check that was conducted on the outlet Panametrics meter at site G.1 is shown in Figure G.2. The following gives an overview of the important issues regarding instrumentation errors which could be introduced into the flowmetering system.

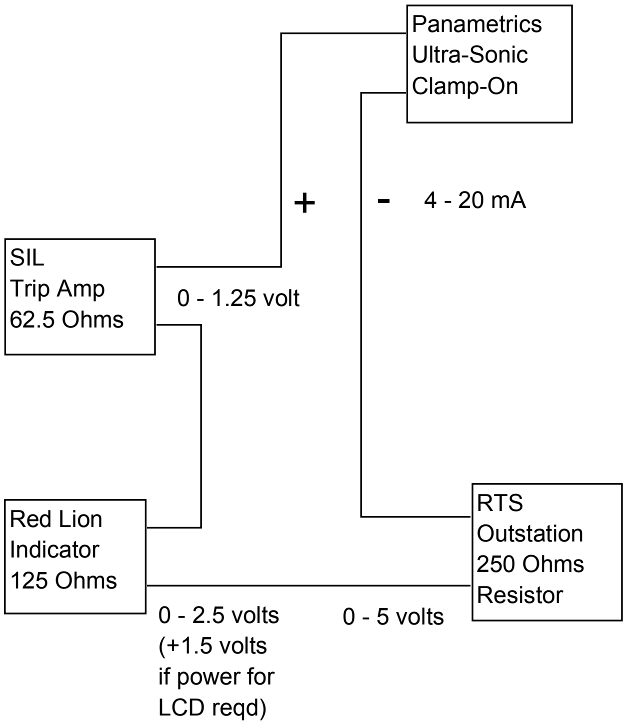


Figure G. 2 Signal Loop for Panametrics Ultrasonic Clamp-on Outlet Meter at Site 1 Reservoir

G.3.1 Sustainable Voltage Drop Across the Meter

The resistance capacity of the outlet meter is 500 ohm. On this basis, it is calculated (V = IR) that for a maximum output current of 20 mA, the meter is capable of supporting 10 Volts. From Figure G.2, the SIL Trip Amp, Red Lion Indicator and Outstation Resistor have associated resistances of 62.5, 125 and 250 ohms, respectively. The summation of these equals 437.5 ohms which is less than the maximum of 500 ohms and gives a net voltage drop at 20 mA of 8.75 Volts. As long as no additional components are connected in the loop the voltage drop across the meter is considered to be sustainable without deterioration of the flow signal.

G.3.2 Additional Components and the Associated Error

One concern, however, is the effect of incorporating an additional component such as an LCD display into the loop. Such a component would have a resistance of around 75 ohms, bringing the total resistance to 512.5 ohms. The voltage required at 20 mA to support this load is now 10.25 Volts which is clearly above the maximum permissible of 10 Volts. The consequence of this is that the maximum output signal (previously 20 mA), has to reduce to 19.51 mA (I = V/R). If the meter had been set up such that the current output at the maximum flow is 20 mA, then the introduction of the additional LCD introduces an error of -2.4%. Furthermore, this error would increase if further components were to be included in the loop.

G.3.3 Conclusions

Errors can be introduced into the loop if the voltage taken by the various components in the system exceeds that sustainable by the meter. An appreciation of this issue is therefore required, particularly where systems may be operating at or close to their maximum capacity.

G.4 ERRORS IN ELECTROMAGNETIC SIGNAL LOOP VIA RADIO AT SITE 2

A block diagram showing typical error sources in the signal loop via radio to that found at the site 2 reservoir, is shown in Figure G.3. A schematic summarising the measurements made (and the subsequent errors) from a site visit to this reservoir is provided in Figure G.4.

G.4.1 Range and Zero Flow Errors With and Without Magmaster Display Connected

Following the procedures detailed in Section G.2.1, simulated flows were generated at the outlet transmitter using a current source simulator. Unlike before, where the maximum flow rate at 20 mA had been scaled to correspond to a flow of 25 tcmd, the maximum output of the meter was set at 17.04 tcmd, (giving a half flow of 8.52 tcmd). This somewhat curious figure is likely to have resulted during the replacement of the electromagnetic meter for the old meter at this site. For example, perhaps the range setting of the new meter was to be set up the same as the old one but the units had changed from imperial to metric. The resulting errors are summarised in Table G.5.

Table G.5 Comparison of Transmitter Errors at Varying Simulated Flowrates

Simulated Flow	Flow (tcmd)	Ideal mA	ACTUAL Loop Connected mA	ACTUAL Loop Connected % Error	ACTUAL Loop Disconnected mA	ACTUAL Loop Disconnected % Error
Zero Flow	0	4	4.002	0.06	4.001	0.03
Half Flow	8.52	12	12.006	0.05	12.004	0.04
Full Flow	17.04	20	20.008	0.04	20.008	0.04

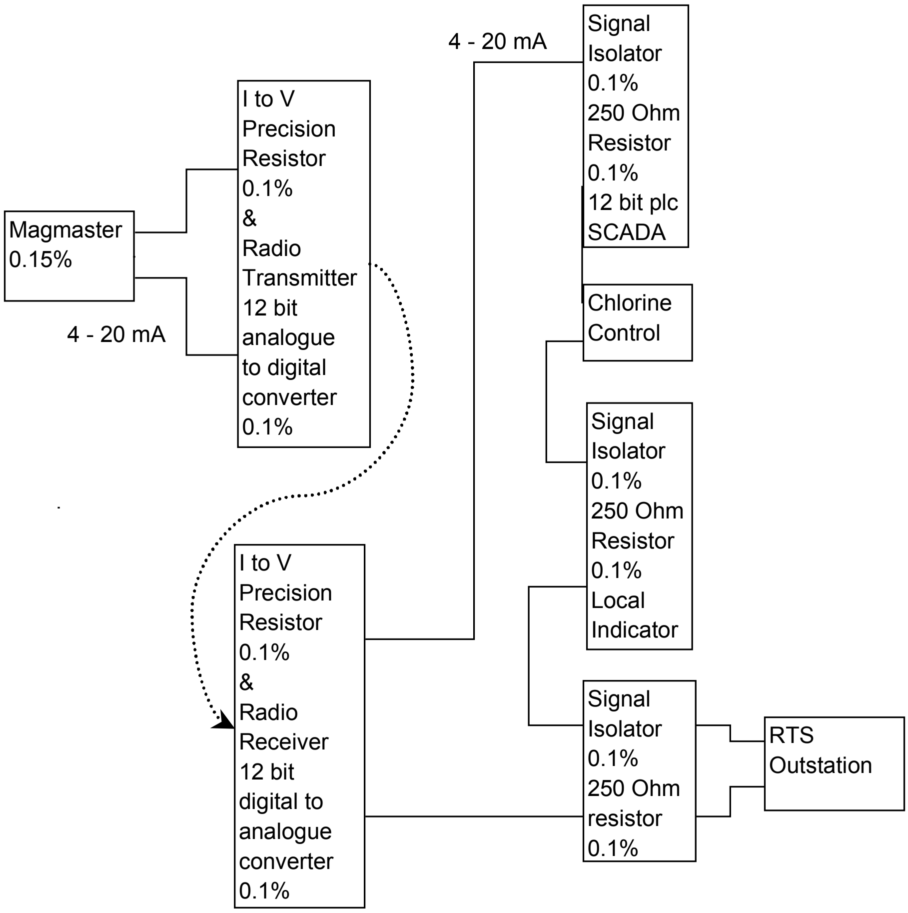


Figure G.3 Typical Flowmeter Signal Loop via Radio

It was noted that signal isolators are invariably used in control loops such as that detailed in Figure G.3 thus ensuring that the mA signal is maintained without significant losses. However, if the loop was dedicated to transferring the flow signal straight to the telemetry outstation then the use of a signal isolator would not be necessary. In most instances in this water company this is not the case and use is made of such signal isolator devices.

G.4.2 Voltage Conversion Errors

Similarly, as described in Section G.2.3, the errors associated with the precision resistor (rating 0.1%) in the conversion of the current to voltage for use in the analogue to digital conversion were also evaluated. These are summarised in Table G.6.

Table G.6 Voltage Conversion Errors

			ACTUAL	
Simulated Flow	**Flow (tcmd)**	**Ideal V**	**V**	**% Error**
Zero Flow	0	1	1.001	0.09
Half Flow	8.52	3	3.003	0.09
Full Flow	17.04	5	5.005	0.09

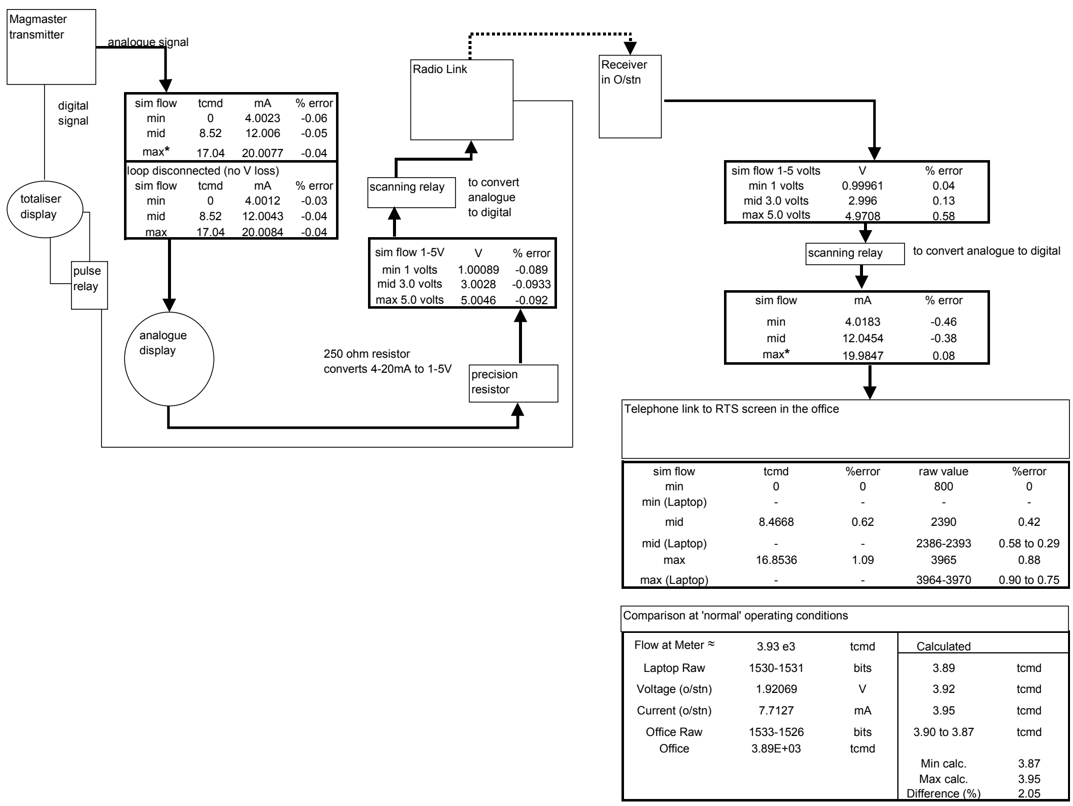


Figure G.4 Electromagnetic Outlet Meter Loop Check at Site 2 Reservoir

G.4.3 Simulated Flow Signals at the Outstation

The radio signal coming into the outstation is first established as a voltage and this digital signal is then processed in the scanning relay to convert it into 4 to 20 mA analogue signal. A comparison of these measured signals with the expected ideal signals are summarised in Tables G.7 and G.8.

Table G. 7 Voltage Measurements in Outstation

			ACTUAL	
Simulated Flow	**Flow (tcmd)**	**Ideal V**	**V**	**% Error**
Zero Flow	0	1	1.000	-0.04
Half Flow	8.52	3	2.996	-0.13
Full Flow	17.04	5	4.971	-0.58

Table G.8 Current Measurements in Outstation

			ACTUAL	
Simulated Flow	**Flow (tcmd)**	**Ideal mA**	**mA**	**% Error**
Zero Flow	0	4	4.018	0.46
Half Flow	8.52	12	12.045	0.38
Full Flow	17.04	20	19.985	-0.08

G.4.4 Telephone Link to RTS Screen in the Office

One of the last checks to be carried out was a comparison of both the tcmd and raw digital value signals (bits) with those received at the outstation. Here, a phone call was made to the office and a water company colleague reported back the readings from the RTS. The tcmd signals were compared with the ideal signals expected for each of the flow ranges examined (zero flow = 0 tcmd, mid flow = 8.52 tcmd and full flow = 17.04 tcmd) and the raw values compared to the data logged on the laptop at the outstation. A summary of the recorded readings and calculated errors is provided in Table G.9.

Table G. 9 RTS (Regional Telemetry System) Outstation Errors

Simulated Flow	Ideal Flow (tcmd)	Measured Flow (tcmd)	% Error	Ideal Count	Measured Count	% Error
Zero Flow	0	0	0.00	800	800	0.00
Half Flow	8.52	8.467	-0.62	2,400	2,390	-0.42
Half Flow (laptop)	-	-	-	2,400	2,386 to 2,393	-0.58 to -0.29
Full Flow	17.04	16.854	-1.09	4,000	3,965	-0.88
Full Flow (laptop)	-	-	-	4,000	3,964 to 3970	-0.90 to -0.75

G.4.5 Comparison at Normal Operating Flowrates

As a final check, the current source simulator was removed and the transmitter reconnected to the primary device. The exercise described in Sections G.4.3 and G.4.4 was then repeated in order to compare the signals under normal operating conditions. The measurements made and resulting errors are summarised in Table G.10.

This exercise is of course complicated by the fact that the flow being measured in the electromagnetic flowmeter is not constant. This makes any assessment of errors in the data path from meter through telemetry more difficult.

Table G.10 Signals and Errors at Normal Operating Flowrates

'Normal' Flow	Measured Readings	Units	Conversion into tcmd	% Error
Flow Measured at Meter	≈ 3.93	tcmd	3.93	-
Laptop Raw at Outstation	1530 to 1531	Bits	3.89[a]	-1.02
Voltage at Outstation	1.921	Volts	3.92[b]	-0.25
Current at Outstation	7.713	mA	3.95[c]	0.51
Office Raw	1533 to 1526	Bits	3.90[d] to 3.87	-0.76 to -1.53
Office Daily Flow	3.89	tcmd	3.89	-1.02

a $=\frac{(1530-800)}{(4000-800)}\times 17.04$; b $=\frac{1.921-1}{(5-1)}\times 17.04$; c $=\frac{(7.713-4)}{(20-4)}\times 17.04$; d $=\frac{(1533-800)}{(4000-800)}\times 17.04$

G.4.6 Conclusions

The 250 ohm resistor used to convert the 4-20 mA signal into a corresponding voltage was this time of the higher precision wire wound type. As described in Section G.2.3, such a resistor has an accuracy rating of ± 0.1%. It can be seen from the errors in Table G.6, that this higher precision resistor has resulted in an overall improvement in the data signal path with errors indeed less than the 0.1% rating of the resistor.

G.5 ERRORS IN INLET ELECTROMAGNETIC METER AT SITE 3 RESERVOIR

Following similar procedures to those detailed in Sections G.2 to G.4, a complete end to end check of an inlet electromagnetic flowmeter at the site 3 reservoir was performed. This site offered a particularly convenient means of checking the flow data path because all the various parts of the system are installed in close proximity to one another. Here, not only is the flowmeter located under the same roof as the flow controller and the telemetry outstation but there are also two computer terminals allowing cross reference of the SCADA and telemetry displays.

Simulated flow signals were generated in the flowmeter at the following nominal levels: 4, 8, 12, 16 and 20 mA. In the first series of measurements, the output indicated by the current source simulator was assumed to be exactly as indicated. These series of measurements are summarised in Section G.5.1. It was then suggested by the water company technician doing the tests that it would be useful to check this input with a 'Fluke' current meter which is traceable to national standards. The measurements described in Section G.5.1 were then repeated but this time the signal generator was adjusted so that the Fluke meter indicated the required nominal current. This series of measurements is summarised in Section G.5.2. The last set of measurements to be made was a check of the signal path directly from the telemetry outstation to the telemetry display. These measurements, which are summarised in Section G.5.3, were made with the current signal generator adjusted so that the Fluke meter indicated the required current.

G.5.1 Signal Check of Flowmeter Through to SCADA and Telemetry With Current As Indicated By the Signal Generator

As detailed in Section G.5, the first series of signal checks was established using the current as indicated by the signal generator. Figure G.5 details the measurements made and the corresponding errors at the various points in the signal path.

Turbo
E-Mag Meter
0 to 300 m3/hr

Flow Controller

mA (Fluke mA)	Expect (m3/hr)	Displayed	Error (%)
4 (4.00)	0	0.00	0.0000
8 (7.99)	75	74.71	-0.3867
12 (11.98)	150	149.80	-0.1333
16 (15.98)	225	225.00	0.0000
20 (19.98)	300	299.70	-0.1000

Telemetry Outstation - Analogue Display (mA)

mA	Expect (mA)	Displayed	Error (%)
4	4	3.9882	0.0000
8	8	7.9989	-0.0138
12	12	11.9961	-0.0325
16	16	16.0070	0.0438
20	20	20.0077	0.0385

Scada Display

mA	Expect (m3/hr)	Displayed	Error (%)
4	0	0	0.0
8	75	75	0.0
12	150	150	0.0
16	225	225	0.0
20	300	300	0.0

Precision Resistor - nominally 250 ohms
(Measured to be 250.178 ohms)

Telemetry Outstation - Analogue Display (V)

mA	Expect (V)	Displayed	Error (%)
4	1	0.9967	0.0000
8	2	1.9993	-0.0350
12	3	2.9930	-0.2333
16	4	4.0018	0.0450
20	5	5.0021	0.0420

Telemetry Display

mA	Expect (m3/hr)	Display (m3/hr)	Error (%)	Expect (Bits)	Display (Bits)	Error (%)
4	0	0	0.0000	800	800	0.0000
8	75	75	0.0000	1600	1600	0.0000
12	150	149.92	-0.0533	2400	2399	-0.0417
16	225	224.92	-0.0356	3200	3199	-0.0313
20	300	299.83	-0.0567	4000	3998	-0.0500

Figure G. 5 Summary of Signal Check With Current As Indicated By the Signal Generator

G.5.2 Signal Check of Flowmeter Through to SCADA and Telemetry With Current Adjusted to Fluke Meter

Again, as detailed in Section G.5, the second series of signal checks was established by adjusting the signal generator so that the Fluke meter indicated the desired value. Figure G.6 details the measurements made and the corresponding errors at the various points in the signal path.

Turbo
E-Mag Meter
0 to 300 m3/hr

Flow Controller

mA (Fluke mA)	Expect (m3/hr)	Displayed	Error (%)
4.00 (4.00)	0	0.00	0.0000
8.01 (8.00)	75	75.085	0.1133
12.01 (12.00)	150	150.00	0.0000
16.01 (16.00)	225	225.10	0.0444
20.02 (20.00)	300	300.20	0.0667

Telemetry Outstation - Analogue Display (mA)

mA	Expect (mA)	Displayed	Error (%)
4	4	3.9920	-0.2000
8	8	8.0072	0.0900
12	12	12.0141	0.1175
16	16	16.0176	0.1100
20	20	20.0303	0.1515

Scada Display

mA	Expect (m3/hr)	Displayed	Error (%)
4	0	0	0.0
8	75	75	0.0
12	150	150	0.0
16	225	225	0.0
20	300	300	0.0

Precision Resistor - nominally 250 ohms
(Measured to be 250.178 ohms)

Telemetry Outstation - Analogue Display (V)

mA	Expect (V)	Displayed	Error (%)
4	1	0.9980	-0.2000
8	2	2.0019	0.0960
12	3	3.0031	0.1033
16	4	4.0045	0.1125
20	5	5.0072	0.1440

Telemetry Display

mA	Expect (m3/hr)	Display (m3/hr)	Error (%)	Expect (Bits)	Display (Bits)	Error (%)
4	0	0	0.0000	800	800	0.0000
8	75	75.375	0.5000	1600	1604	0.2500
12	150	150.281	0.1873	2400	2403	0.1250
16	225	225.188	0.0836	3200	3202	0.0625
20	300	300.094	0.0313	4000	4001	0.0250

Figure G.6 Summary of Signal Check With Current Adjusted to Fluke Meter

G.5.3 Signal Check of Telemetry Outstation Through to Telemetry

Again, as indicated in Section G.5, the signal path directly from the telemetry outstation to the telemetry display was checked by applying the current signal generator directly to the point in the telemetry outstation where the flow signal would normally be processed.

Telemetry Display With Simulated Current at Outstation

mA (Fluke mA)	Expect (m3/hr)	Display (m3/hr)	Error (%)	Expect (Bits)	Display (Bits)	Error (%)
3.999 (4.00)	0	0	0.0000	800	800	0.0000
8.000 (8.00)	75	75.281	0.3747	1600	1603	0.1875
12.0004 (12.00)	150	150.00	0.0000	2400	2400	0.0000
16.0010 (16.00)	225	224.719	-0.1249	3200	3197	-0.0938
19.9961 (20.00)	300	299.438	-0.1873	4000	3994	-0.1500

Figure G. 7 Summary of Signal Check of Telemetry Outstation Through to Telemetry

G.5.4 Conclusions

Overall, the flow signal checks summarised in Figures G.5 to G.7 indicate that the data path from the inlet electromagnetic flowmeter at the site 3 reservoir through to telemetry is very good. The largest discrepancy between expected signal and actual signal is in Figure G.6 where an error of 0.50% is calculated between the telemetry flowrate display of 75.375 m^3/hr compared to the expected figure of 75.0 m^3/hr. One reason suggested for this difference is the signal isolator in the flow controller which may possibly be out of linearity.

Once the flow signal is converted into a digital signal it is accepted that no further errors will result as long as this signal is maintained in a digital format. Perusal of the signal checks summarised in Figures G.5 to G.7 indicates that the largest error in any of the digital displays occurred at the same 8 mA signal described above. Here, the 75.0 m^3/hr flowrate should correspond to a digital display of 1600 bits but a figure of 1604 bits was obtained. This results in a discrepancy of 0.25%.

The resistor, as detailed in Figures G.5 and G.6, was measured to be 250.178 ohms. This compares to the 250 $\pm$ 0.1% ohms value that is required from such a wire wound precision resistor. This difference of 0.178 ohms represents a difference of 0.07% indicating that the resistor is within the required tolerance (< 0.1%).

Lastly, the SCADA errors, as indicated in Figures G.5 and G.6, are all shown to be zero. It is noted however that this signal path should not necessarily be considered superior to the signal displayed on telemetry; the reason for the SCADA signal indicating zero error is due to the resolution of the display and in this case having been rounded down to zero. It should therefore be borne in mind that an exercise like this might indicate larger errors than expected if the errors happened to be rounded upwards.

G.6 CONCLUSIONS OVERALL

Following three separate site visits to the water company a number of signal data paths have been investigated in order to identify and quantify the errors that can be introduced.

From the tests performed at the inlet electromagnetic meter at site 1, the worst error between the RTS screen and the Magmaster transmitter output was calculated to be 0.64%. At this site it was found that the resistor used to convert the mA signal to a voltage was not of the wire wound precision type. Instead, a ceramic resistor with a tolerance of $\pm$ 0.5% had been installed and the resulting maximum voltage error of 0.4% is consistent with this finding. If a higher precision resistor was installed instead this error would reduce to below 0.1%.

From an assessment of the clamp-on ultrasonic meter at site 1 it is concluded that care has to be taken when including additional components into the signal loop such as an LCD. It is calculated that if such a component were to be added to the present system then an error at maximum flowrate of 2.4% would be introduced. The reason for this is that the resistance capacity of the meter (around 500 ohms) is below the total loading on the system when the LCD is connected.

Errors were also calculated at the electromagnetic meter at site 2. This site introduced extra uncertainties due to the radio link between the signal transmitter at the meter and the receiver at the outstation. The 250 ohm resistor used at this site to convert the 4-20 mA signal into a corresponding voltage is this time of the higher precision wire wound type. The resulting signal errors in the voltage conversion are now shown to be less than 0.1%, consistent with the performance rating of the resistor. A comparison of the signals received at the outstation with the signals on RTS indicated that errors of around 1% were produced.

Lastly, signal checks were also carried out on the inlet electromagnetic flowmeter at the site 3 reservoir. The largest discrepancy between expected and recorded signals was found to be 0.50% and represents the difference between the telemetry outstation and RTS displays. One reason suggested for this difference is the signal isolator in the flow controller which may possibly be out of linearity.

Once the flow signal is converted into a digital signal it is recognised that no further errors will result as long as this signal is maintained in a digital format. Perusal of the measurements indicate that largest error in any of the digital values occurred at the same conditions that resulted in the error of 0.50% described above. Here, the 75.0 m^3/hr flowrate should correspond to a digital display of 1600 bits but a figure of 1604 bits was obtained, a discrepancy of 0.25%. Again, the precision resistor was measured to be 250.178 ohms and is within the specified tolerance of $\pm$ 0.1% ohms.

During the same visit to site 3 reservoir, the flow signal was also traced through the SCADA system. Here, it was found that the SCADA signal indicated no error at all. The reason for this is considered to be due to the poor resolution of the display and in this case the difference between the SCADA signal and the expected digital count was less than half of one flow unit (m3/hr) and so the SCADA display has been rounded down to zero. It should therefore be borne in mind that an exercise like this might indicate larger errors than expected if the difference is greater than half of one flow unit resulting in the SCADA display rounding upwards.

It is concluded that errors are introduced into the signal in the data path from meter through to telemetry. Although the errors at the three sites investigated may appear to be reasonably small, it is still considered important that procedures such as those carried out should be performed. This will allow any problems in the data path to be highlighted at an early stage and, if such procedures are performed regularly, will provide ongoing confidence that the data path is reliable.

G.7 FURTHER READING

In keeping with the collaboration which has existed between all parties involved in this project, Anglian Water kindly made available a report which they considered could be valuable to this case study. This was indeed found to be the case, and in the following Appendix G1, a short report has been prepared which makes close reference to this work. This appendix introduces and describes the main data quality issues arising from flowmeter data acquired using telemetry.

APPENDIX G1 –

TELEMETRY DATA QUALITY ISSUES: THE EXPERIENCE OF ANGLIAN WATER

G1.1 Introduction

This short report aims to introduce and describe the main data quality issues arising from flowmeter data acquired using telemetry. It has been put together with close reference to the 'Water Balance Distribution Input'[1] report by Godfrey Pool and G. Gelley (1999) which has kindly been made available by Anglian Water to the WM04 project for the purposes of this case study into the 'Analysis of the Data Path From Meter Through Telemetry'. The following represents a summary of the main issues discussed in this Anglian Water report[1].

The Anglian Water report[1] discusses an earlier package of work which they undertook and which was aimed at investigating quality assurance of the Distribution Input statistics provided to the water balance. Due to the unknown accuracy of meters, and to avoid duplication of effort, this study concluded that work should be concentrated on flowmetering issues other than those relating to the accuracy of the primary device. In the new work, instead, the focus was on the processes of capturing the data and the transfer of this data and information to the final users.

Despite a semi-automatic data management system being employed by Anglian Water employ throughout their region, there are a number of data quality issues that have arisen. The following summarises the three main areas where there are concerns with regards to the quality of flowmeter data acquired using telemetry.

G1.2 Flowmeter Issues

It is of course recognised that the fundamental factor affecting the quality of flowmeter data is the accuracy of the primary measuring device. Opinions were expressed from a number of works managers and maintenance engineers that there was a high level of confidence in the accuracy of the meters and that it was considered that the meters were operating within manufacturers rated tolerances (± 2%). The potential for meters to drift out of calibration was not a concern since it was viewed that as long as the meters did not fail they would maintain the same level of accuracy. Following detailed surveys of the top 23 Water into Supply sites Anglian Water now acknowledge that, although some works managers may hold this view, this is very optimistic; it is considered more likely that their meters are in a 3 to 7% accuracy range.

The diversity of flowmeters from different manufacturers, particularly where meters are now obsolete, creates problems in obtaining secondary device simulators with which to verify the secondary devices. In older installations where flow integrations are performed on site with a separate site integrator, a concern is also raised from comparison of these integrations with the integrated signals derived at the telemetry outstations. This is due to the comparisons stated not being performed on a like-with-like basis. As such old meters are replaced it is however described that this is becoming less of a problem.

Another concern relates to the comparison of site readings with telemetry and the inability to perform this task locally, since there is a requirement to communicate in real time with someone back in the office at a workstation.

A number of potential problems have also been highlighted with regard to the installation of new meters; correct wiring, correct identification, correct scaling and calibration. It is highlighted however that where the meter is being connected to telemetry, the commissioning process should ensure that these issues are avoided.

Another issue relates to the need for good communication between the various departments in the business. For example, the commissioning of a new meter may be the responsibility of the Business System Owner but there is a requirement to inform the Telemetry Manager that a new meter has been installed. One recommendation in Anglian Water[1] to improve such communication is for the data verifiers to have instrumentation responsibilities. A number of occasions throughout the report stress the need to be clear which members of staff are accountable for informing the telemetry team when changes are made to flowmeters on site.

G1.3 Telemetry Issues

The main cause of inaccuracies with telemetry, recognised by Anglian Water[1], is inadequate checking of the telemetry integration sequence. The volumetric flow passing through a meter is calculated daily at the outstation by integrating the instantaneous flows recorded throughout the day. Whenever a new meter is commissioned or an adjustment is made to a meter, this integrated flow has to be checked against the meter's own integration at the site. Anglian Water[1] suggest that this comparison should be conducted over a period in excess of 24 hours. If the telemetry integration is not checked with the flowmeter output, or the volumetric results are not within $\pm$ 2% of each other, it is suggested that some of the following problems may be going undetected:

- incorrect scaling of the real or derived points;
- incorrect mapping;
- incorrect identification of the correct analogue signal leading to the wrong point being integrated on telemetry;
- Problems with the analogue card in the outstation;
- Incorrect archiving of daily totals on the telemetry system database;
- Inaccuracies between site integrator readings and current output from instantaneous flowmeter;
- Positive meter zero errors are a problem because the flow integration sequence counts these values.

Anglian Water[1] conclude that the checking of the telemetry integration sequence be covered by a telemetry QA procedure. The resource implications of this, whereby two site readings are required over the $\approx$ 24 hour period, is recognised as an important issue and is the main reason for this check not being performed as a matter of course. Following recent discussions with Anglian Water they indicated that this procedure is now being carried out whenever a new meter is commissioned. They have also just initiated a program of meter verification work looking at their top 1200 meters where this, along with other checks, will be carried out on a regular basis by contractors.

Furthermore, there is also an issue regarding the accuracy of comparing an instantaneous meter reading on site with the telemetry reading obtained from having taken a split second snapshot. Anglian Water recommend that best comparisons will be achieved when the site reading, either from a real flow or current input, maintains a steady value for at least 1 to 2 minutes.

Flow data are downloaded from the telemetry outstations once daily. If the outstation signal is reset (or the sequence is reloaded) then the total flow prior to this event is lost. Anglian Water[1] suggest that one way around this problem would be to suitably *flag* this data so that the telemetry people working with the data would know that it was 'invalid'. This could also be used to trigger an alarm or automatic e-mail circulation to the appropriate member of staff who has to be informed.

G1.4 Data Verification Issues

One particular procedure that has been highlighted as adversely affecting data quality is the practice of data owners/verifiers pointlessly overwriting perfectly valid telemetry data. This issue arises from sites where separate integrators have been used over say weekly or fortnightly intervals to calculate total volumetric flow - from this information it is of course a trivial task to calculate an average daily flow. It is the procedure of changing the valid daily telemetry data with this daily average flow that has been highlighted as inappropriate. Here, instead of the database being populated by perfectly good telemetry data over the time period of interest (7 or 14 days), a series of identical daily average values may have been entered instead.

Anglian Water[1] report that they have introduced controls to limit such manual alteration to telemetry data on the database. The only member of staff authorised to perform such operations is the SWORPS (Source Works Output Reporting System) data owner. Following implementation of this policy the proportion of data requiring to be manually altered on their system has reduced by around two thirds.

To aid the procedure of checking the telemetry data an automatic verification process has been put in place whereby telemetry data is compared to set limits. These limits are defined from the statistical analysis of accepted data from seasonal, weekly, daily and rate of change variations. In real terms, the reduction in manually altered data together with the automatic verification procedures has resulted in an increase of 10% of the data passing verification. Furthermore, Anglian Water[1] appreciate the benefits introduced by their data verification procedures; instead of this task predominantly being clerical, it has very much taken on a problem solving role.

Although the automatic procedures described by Anglian Water[1] have been highlighted as providing an efficient means of verifying their telemetry data, concerns were raised that some poor quality data may be unwittingly being assessed as valid. In order to investigate this issue Anglian Water[1] studied two months worth of data from all their sworps sites manually. The conclusion from this analysis was that around 10% of the sites had an occasion when a significantly low, (and incorrect) daily volume had passed through verification undetected. This is likely to be due to outstation resets or sequence reloads, as previously discussed, where the flow prior to these changes is lost.

<u>References</u>

1 'Water Balance Distribution Input' - report by Godfrey Pool and G. Gelley Anglian Water, (1999).

APPENDIX H

CASE STUDY REPORT:
ANALYSIS OF DATA FROM WATER METERS

EXECUTIVE SUMMARY – APPENDIX H

Flow metering and data logging technology are areas where the UK water industry is currently making large investments. As a result, large quantities of flow data are being produced and, if these data are to be used to best advantage, the industry must identify effective methods of data analysis. The National Engineering Laboratory has undertaken an examination of a number of typical data sets provided by a water company and this report describes the methods of data analysis performed and the major findings.

The main conclusion resulting from this work is that the application of data analysis techniques can extract a great deal of information from flow meter data. The report demonstrates also that major benefits can be obtained if data assessment and analysis are performed as the data is being acquired. The major advantage of such real-time analysis is that it could be run automatically and would result in metering and operational problems being identified more quickly than at present.

One technique which stands out from this work as showing particular potential is the application of Cusums. This statistical method allows changes in mean level in a noisy signal to be highlighted and quantified. This could help identify whether the reasons for the unexpected data were operational changes, faults or data collection problems.

One set of data studied was shown to be marred by data collection problems relating to the range settings for the computer logging equipment. Recommendations have been made to ensure that the flowmeter signals always would remain within the range of the logging equipment and that the logging equipment is functioning correctly.

In the assessment of the metered data at a water treatment works, independent mass balances on the abstraction and supply sides yielded some interesting findings in terms of the relationship between the imbalance and the ratio of the borehole abstraction rates. However, much more useful information was obtained when a system mass balance across the whole abstraction-supply system was considered. This analysis made it possible for the accuracy of the individual flowmeters in the system to be assessed, and a simple control chart approach to plotting meter corrections was shown to provide an immediate warning of a disturbance in the system.

CONTENTS

H.1 INTRODUCTION

The UK water industry is currently making large investments in new flow metering and data logging technology. As a result large quantities of flow data can now be collected but if these data are to be used to best advantage the industry must identify effective methods of data analysis. NEL was contracted to carry out an examination of typical data sets and identify methods of data analysis that will increase the value to the industry of their investment in new technology.

The funding for this research was provided by the UK's Department of Trade and Industry through the NMSPU (National Measurement System Policy Unit) 1999-2002 Flow Programme, together with co-funding from a number of water companies: Anglian Water, Dwr Cymru, Northumbrian Water, Southern Water, Thames Water and Yorkshire Water. The major advantage to be gained from this collaboration with the water companies is the direction and support they have provided, ensuring that the research is carried out with a focus on issues of particular industrial relevance. A major part of this project was to undertake a number of case studies and this report presents the findings from one such study carried out for one of the water companies.

As part of this study the water company supplied NEL with a number of data files from their meter logging system for analysis. This report describes the findings from three separate areas of investigation which have ben undertaken based on these sets of data.

H.2 CASE STUDY 1 - DATA FILE 'WESTWS'

This file contains data from an abstraction meter, labelled 'borehole 2', entering a water treatment works. The data were recorded at 15-min intervals over the period 19 March 2000 to 5 September 2000. Figure H.1 shows a plot of the entire data file. There are a number of striking features of this signal:

1) the extremely flat profile of the high level signal at 51.5 units,
2) the absence of any high level signal in the period 8 July to 24 August, and
3) the extended period of negative signals between 24 August and 1 September.

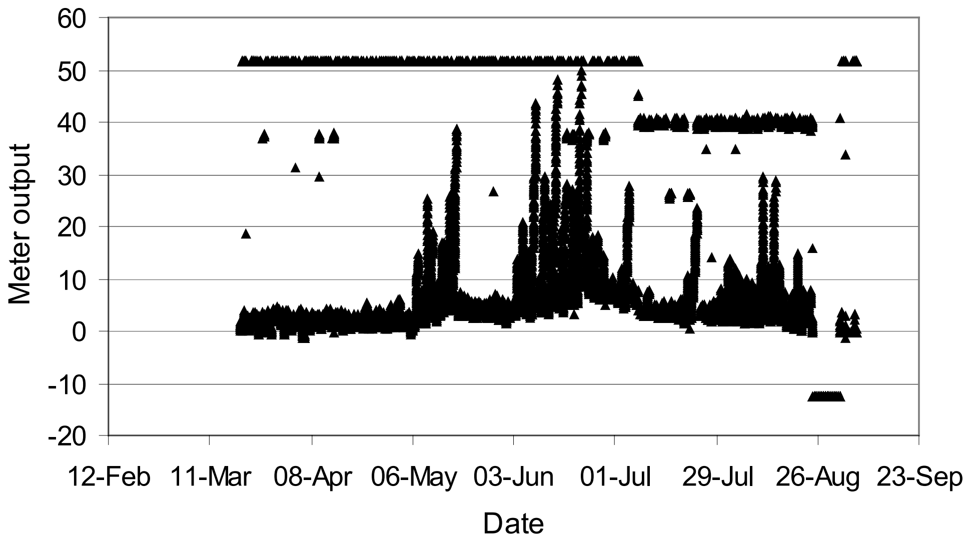


Figure H.1 Raw Data From 'WestWS' File at 15-Minute Intervals

Considering the "51.5" unit signal first, examination of the data shows that for hours at a time the flowrate was apparently 51.484 units without wavering. The smallest difference between output values in the period when the signal was changing was about 0.015 units, or 0.03% of the 51.5 level. It seems highly unlikely that the flow and the instrument would be as stable as this and the suspicion must be that the signal has saturated the analogue-to-digital (A-to-D) converter, either as a result of the flow exceeding the maximum value recordable by the converter or due to a fault in the converter system. Further evidence of this can be seen from the difference in output between the lowest (-12.5) and the highest (51.484) signals. The average value of the smallest step is 0.01556 giving 4114 steps between the highest and lowest recorded values; this is very close to the 4096 (or 2^{12}) steps of a 12-bit A-to-D converter. Whether the signal is saturated by being set for a flow below the maximum seen at the meter, or whether the apparent saturation is due to signal problems can only be a matter of conjecture. However, the problem could be detected at a very early stage by screening all data at the time they are recorded to check for saturation. In this way saturation would be detected within 15 mins of the first fault and, even if it was decided that no action would be taken until 10 successive readings were at the saturation level, action could be taken within 2.5 hours of the problem occurring.

The period from 8 July to 24 August exhibits no flow readings at the extremes of a 12-bit A-to-D converter range, which suggests that this is potentially a period of clean signal. A closer view of the data (Figure H.2) reveals an operating cycle that does not appear to be a daily cycle and this would need to be interpreted against the expected operating cycle for the plant. The very long slow rise in flow from 00:15 on 22 July to 17:45 on 23 July also needs to be verified against the operation of the plant.

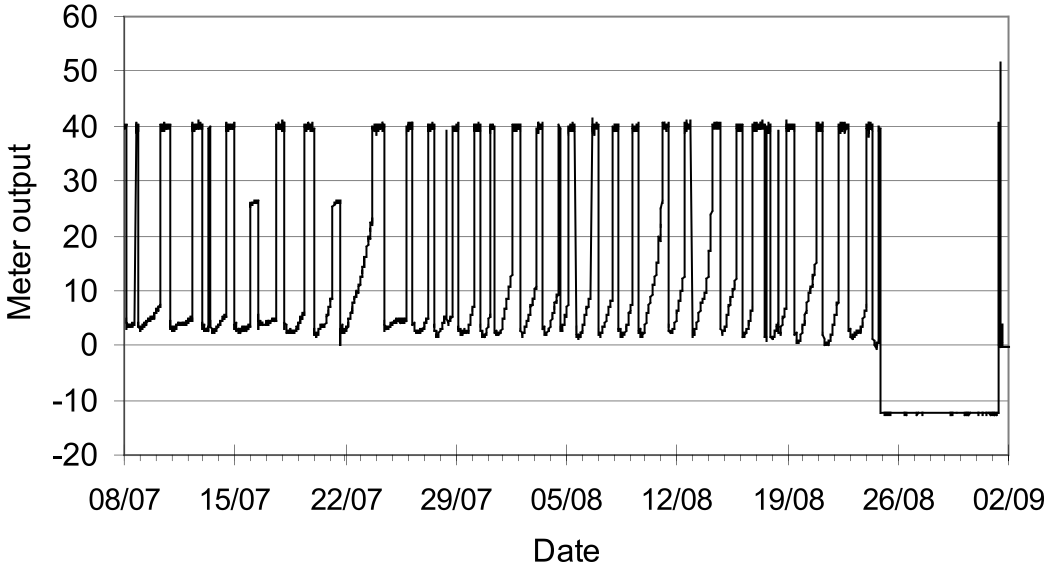


Figure H.2 Detailed View of 'WestWS' Data

The period of steady negative reading from 20:15 on 24 August to 09:00 on 1 September shows only the very occasional step change by 0.015 units and appears to indicate that either the instrument or the logging system was off line in this period. The alternative scenario of a genuine negative flow requires a bi-directional meter but also suggests saturation. Assuming that a negative flow has no meaning in the context of this instrument, this period shows clearly the value of offsetting the meter signal to ensure that zero flows can be distinguished from zero output.

In summary the recommendations from this case study are:

1. all signals should be scaled in a way that permits zero flow to be differentiated from zero signal, by offsetting the signals so that a zero signal represents a small negative flow even when negative flows are impossible;
2. all signals should be scaled in a way that the maximum plant flow is less than the saturated level of the A-D converter,
3. each data point should be screened at the time of recording to identify zero and saturated signals, and
4. data should be screened at the time of recording for departures from the expected operating cycle by, for example, comparing flow with pump settings or with average levels at that time of day.

H.3 CASE STUDY 2 - DATA FILE 'BURYWS'

This file contains data from another abstraction meter. The data were recorded at 15-minute intervals over the period 18 December 1998 to 19 February 1999. Figure H.3 shows a plot of the entire data file. The signals are characterised by obvious banding at approximately 120, 65 and 0 units and these levels were checked to ensure that this was not due to the saturation effects seen in the first study. Variation was present at all levels and the maximum level was about 2600 times the smallest step of approximately 0.04 suggesting that the data were being correctly collected by the logging system.

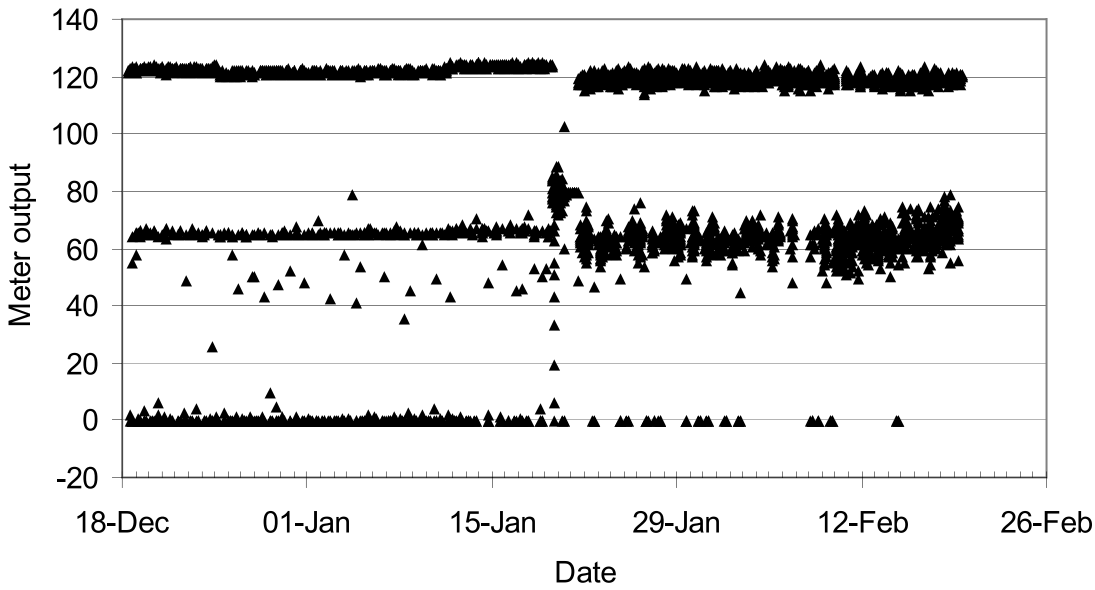


Figure H.3 Raw Data from 'BuryWS' Data File at 15-Minute Intervals

Apart from the banding effects, the signal of Figure H.3 shows that the pattern of flows changed with time, with distinct differences in the banding structure between the period 18 December to 19 January and 21 January to 19 February. The period 19 -21 January appears not to fit closely with either pattern.

Examining the period 18 December to 19 January first, Figure H.4 shows typical daily cycles (for the period 4 – 9 January). These exhibit two periods of high flow in each 24-hour period with quiescent periods in between. During the high flow periods the flow is very uniform though, as noted earlier, it did vary somewhat: this suggests a pumped storage system.

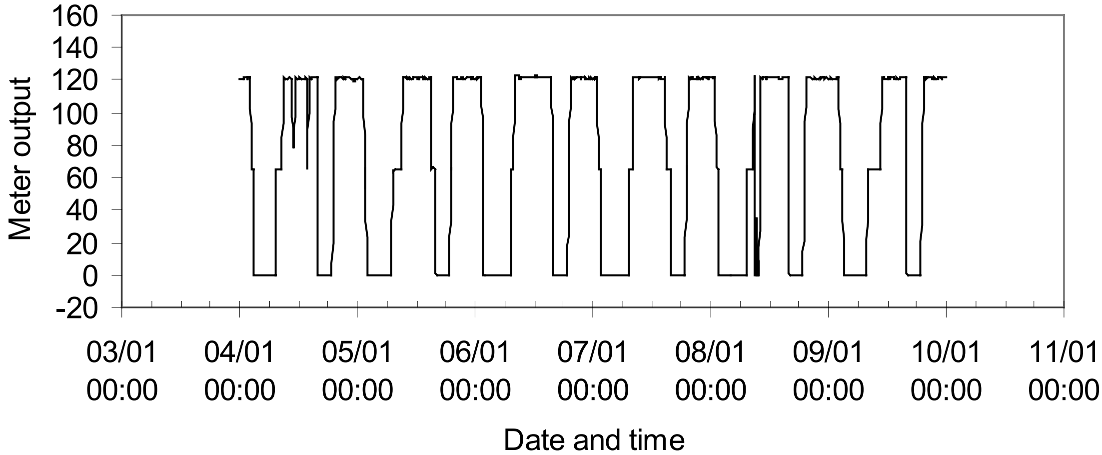
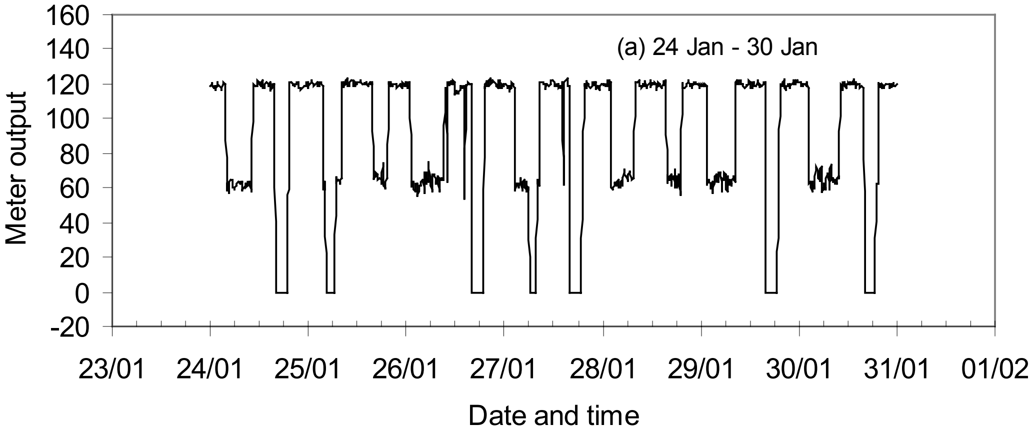


Figure H.4 Detail of 'BuryWS' Data for Period 4 January to 9 January



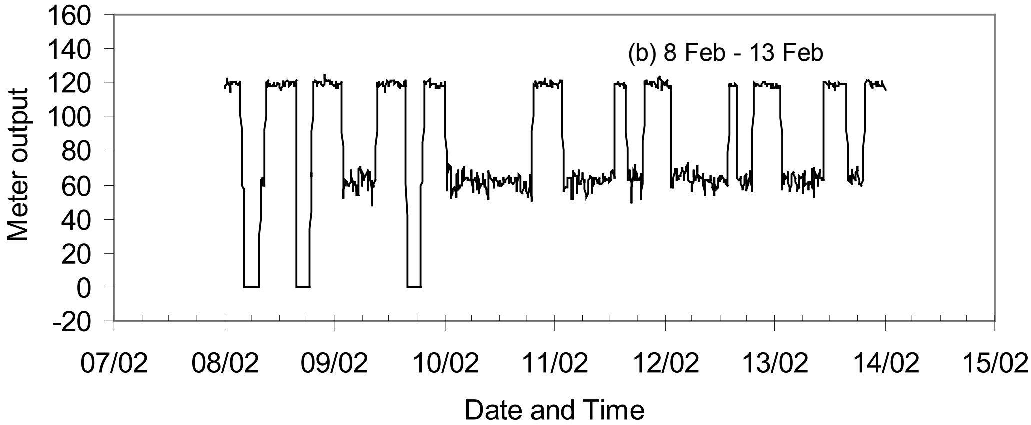


Figure H.5 Details of 'BuryWS' Data for Period 21 January to 19 February

Figure H.5 shows typical traces from the period 21 January to 19 February and show a very different operating cycle. In this period the system was running at two levels, 120 and 60 units, with only an occasional short period of zero flow; this suggests that the system actually operates with two pumps and that, while single pump operation was common after 21 January, it was not used for any substantial periods of time in the period before 19 January.

Figure H.6 shows traces from the period 19 – 21 January; the period, as described earlier, that does not fit closely with either of the patterns discussed so far. This shows a long period (over 24 hours) at a flow of 79 units, a level not encountered at any other time in the two-month period. This could indicate a problem with one pump but the very steady flow suggests a data collection problem. A detailed examination of the signal during this 24-hour period shows that the level of 79 units represents a drop of approximately 1020 minimum signal steps from the previous maxima of around 120 units (1020 ≈ (120-79)/0.04). This points to a problem with the A-to-D converter bit representing 2^{10} (1024) bits. The signal is also very steady in the period; close examination shows that there is variation at the level of 1 or 2 data steps but not any higher level. This reinforces the view that the A-to-D card is not working correctly. As in study 1, screening the data against the operating cycle would have identified an unexpected flow rate in a pumped system and the fault could have been flagged within a short space of time.

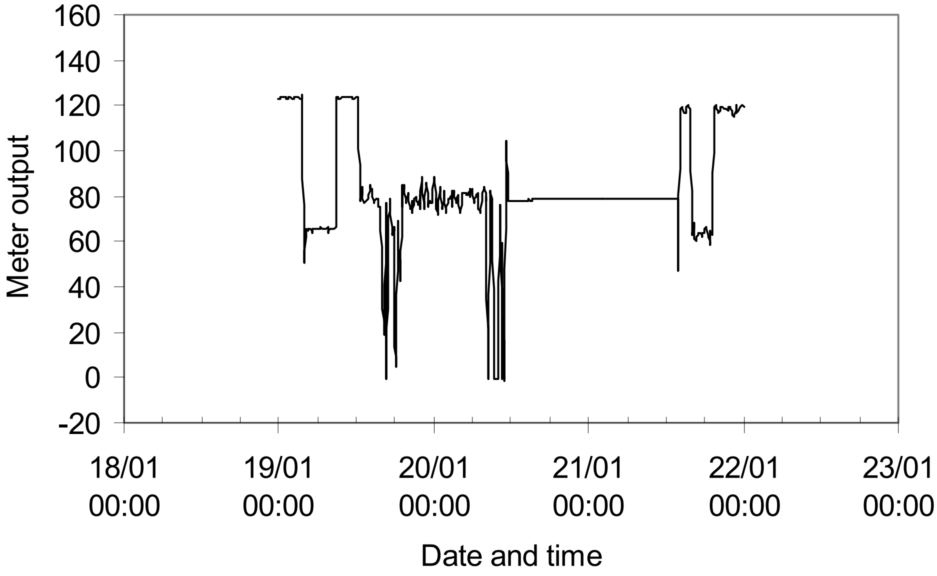


Figure H.6 Detail of 'BuryWS' For Period 19 to 21 January

The differing flow patterns over the period of the data file suggest possible effects on total flow. Figure H.7 shows cumulative flow per 24-hour period and shows considerable day-to-day variation. There are suggestions of changes in level on 25 December, 13 January and 7 February. These were investigated in more detail by plotting Cusums of the variation from the overall daily mean flow. The Cusum technique (Reference 1,2) is a statistical method for highlighting changes in mean level in a noisy signal. The results are shown in Figure H.8. Where the gradient of the Cusum line changes is an indication of a change in the mean level and such changes are apparent on 25 December, 13 January, 2 February and 7 February. The change on 25 December is significant at the 95% confidence level and the other changes are significant at the 99% confidence level. It is interesting to note that the radically different daily cycles across the period 18 – 23 January show no effect on the total flow either on Figure H.7 or on the more sensitive Cusum plot of Figure H.8. It is also interesting that the most significant shift in mean flow, on 13 January, is not apparent from the broad plot of Figure H.3. Even focussing in on the individual daily cycles (Figure H.9), only moderate changes in the cycle can be seen, and even then not on every day after the rise in flow.

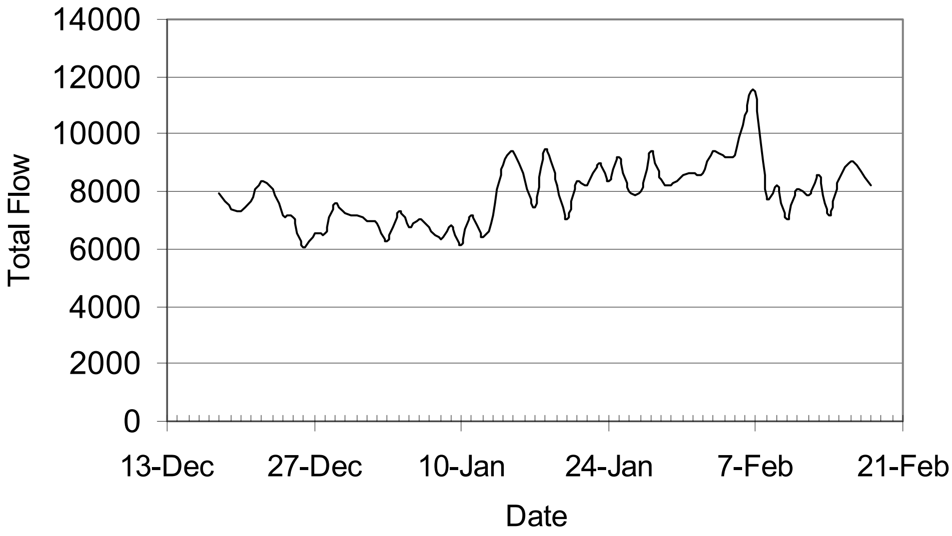


Figure H.7 Total Daily Flows for 'BuryWS' in the Period 18 December to 19 February

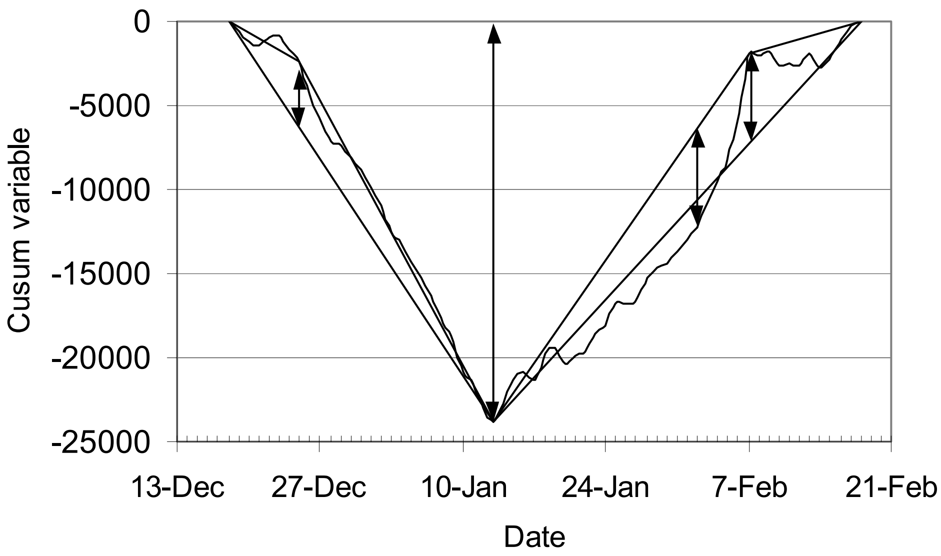


Figure H.8 Cusum Plot of Variation of Daily Water Consumption for 'BuryWS'

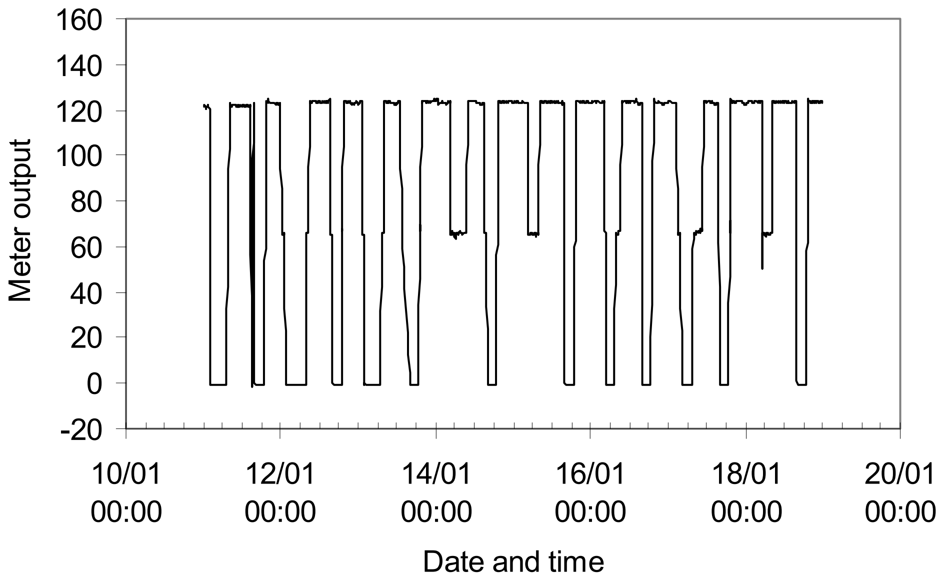


Figure H.9 Detail of 'BuryWS' Data for Period 11 to 18 January

The drop in usage on 25 December might have been expected, and the continuation of low consumption until 13 January was presumably due to an extended shutdown at a major industrial user. The increase in total flow on 13 January is possibly the result of the end of that shutdown but, with levels above the mean level for the pre-Christmas period and for the period following 7 February, a substantial leak cannot be ruled out. Leakage must also be a possibility for the additional increase seen on 2 February. With a simple application of the Cusum technique it should have been possible to identify the changes in mean flow within about 2 – 3 days and a more sophisticated application based on the operating cycle within the 24-hour periods may well have allowed the changes to be detected more quickly. Liaison with major industrial users would then have helped to pinpoint the causes of the changes.

In summary the recommendations of this case study are:

1. data should be screened against the operating cycle, eg pump operation, to ensure that the flowrates are as expected,
2. unexpected levels should be screened to identify the magnitude of shifts and so identify whether the shifts represent operational faults or data collection problems,
3. plotting techniques such as Cusums of period totals should be used to identify changes in total flow, and
4. liaison should be maintained with large users to ensure that significant changes in usage do not result in expensive false alarms in the examination of the metering data.

H.4 CASE STUDY 3 - DATA FILES 'BOURNE LARS' AND 'BOURNE SWORPS'

These data represent the flows into and out of a water treatment works. The case study was divided into three parts. First the abstraction data were analysed on a stand-alone basis; secondly, the water-into-supply data were considered in isolation; and lastly, the case study was concluded by assessing both abstraction and output together in a system balance approach.

(a) Abstraction

The 'Bourne Lars' file contains data from the input meters at the water treatment works. This works has two boreholes feeding into a common header for delivery to the works. Each borehole flow has its own meter and the combined flow is also metered before entering the works system. Figure H.10 shows a schematic of the inlet system. The borehole meters were numbered in accordance with the water company's classification.

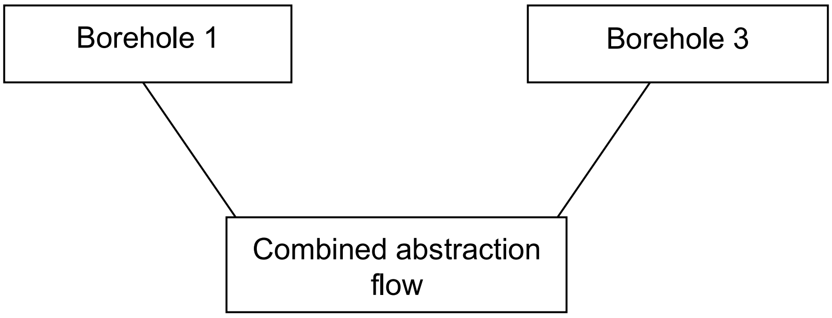


Figure H.10 Schematic of 'Bourne Lars' Metering System

The data from all three meters (Figure H.11) were screened for the types of faults seen in the earlier case studies, no such problems were detected.

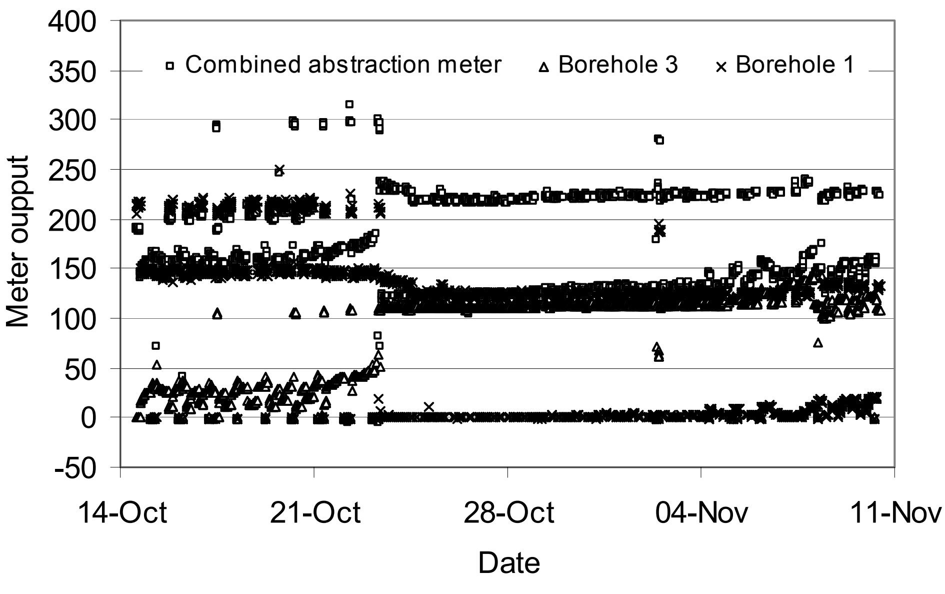


Figure H.11 Raw Data from 'Bourne Lars' Meter

As shown in Figure H.10 the principle of the conservation of mass requires that the combined flow be the sum of the two borehole flows. However, measurement uncertainty dictates that the meter outputs will never balance exactly and Figure H.12 shows the extent of the apparent imbalance. The imbalance is clearly not always in the same direction and there was a significant change in the patterns on or about 23 October. Within each daily cycle there are large changes in the total flow into the treatment works and Figure H.13 shows the imbalance plotted as a function of the total flow. This shows that the direction of the imbalance is dependent on the total flow, with high flows resulting in the combined meter output being less than the sum of the borehole meters, while at lower flows the combined meter output exceeds the sum of the individual meters. Figure H.14 shows the imbalance as a function of the difference between the two borehole flows; when the flow comes principally from 'borehole 3' the combined flow meter over-reads while when the flow is dominantly from 'borehole 1' the combined meter tends to under-read.

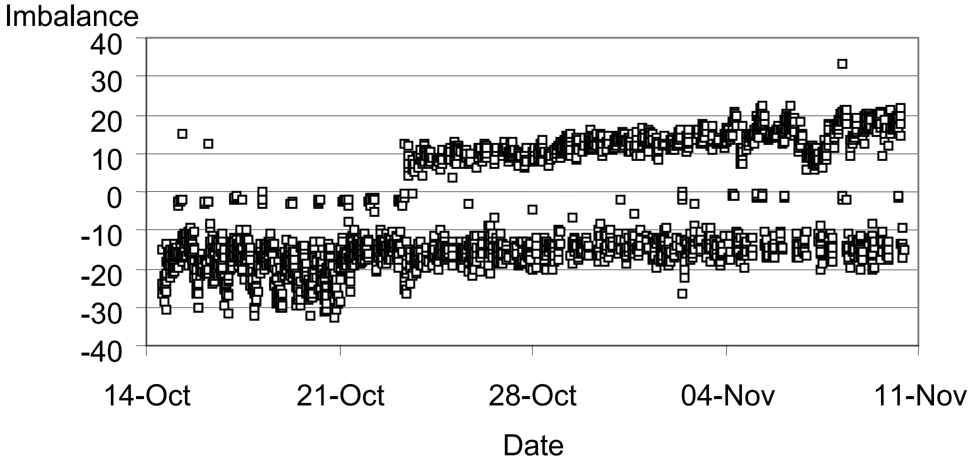


Figure H.12 Imbalance Between Sum of Borehole Meters Combined Meter

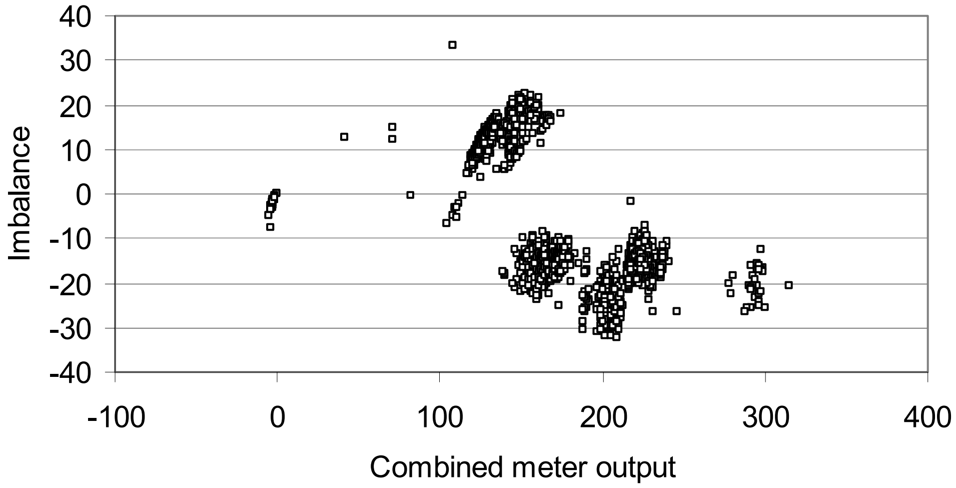


Figure H.13 Imbalance as a Function of Combined Meter Flow

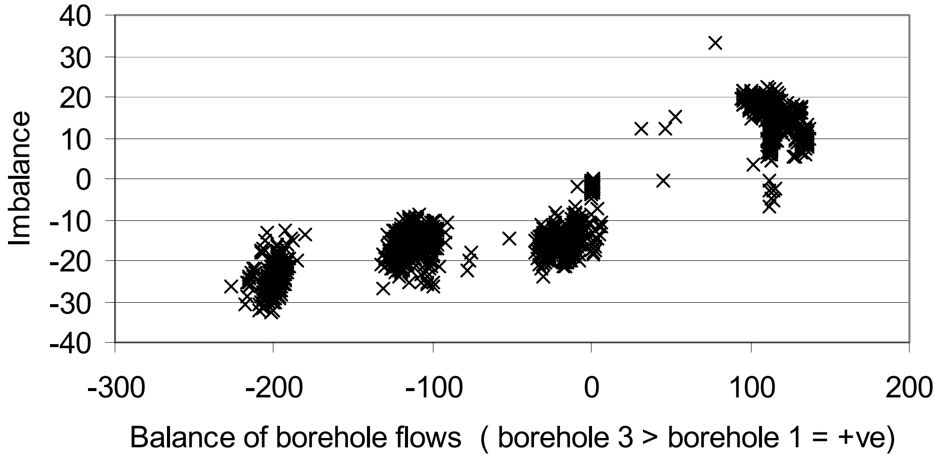


Figure H.14 Imbalance as a Function of the Difference Between Borehole Flows

The trends of Figures H.13 and H.14 are strongly suggestive of an installation effect on the combined flow meter; however, it is understood that the meter is some long distance from the point at which the two flows meet.

(b) Treament Works output

The 'Bourne Sworps' data file contains data from the meters on the output side of treatment works. Figure H.15 shows the layout of the metering system. The raw data are shown in Figure H.16 and no data collection problems were detected. Figure H.16 shows that the bulk of the works output goes to the Toft/Spalding flow and that only small amounts of water are used in the local Bourne area. Figure H.17 shows that the imbalance is small in comparison with the abstraction imbalance shown on Figure H.12 and fluctuates either side of zero. This suggests that the imbalance is due largely to random effects in the metered signals rather than to a shift or bias error in any one meter.

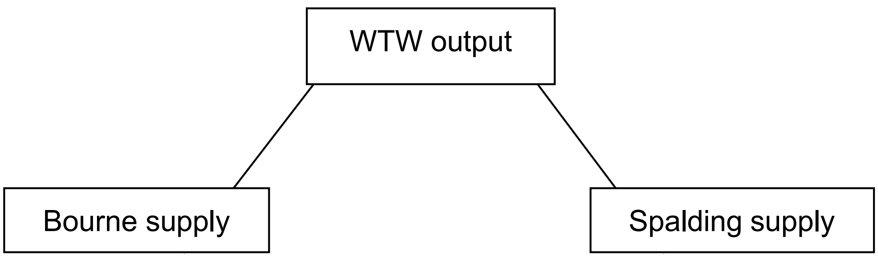


Figure H.15 Schematic of Bourne Sworps Metering System

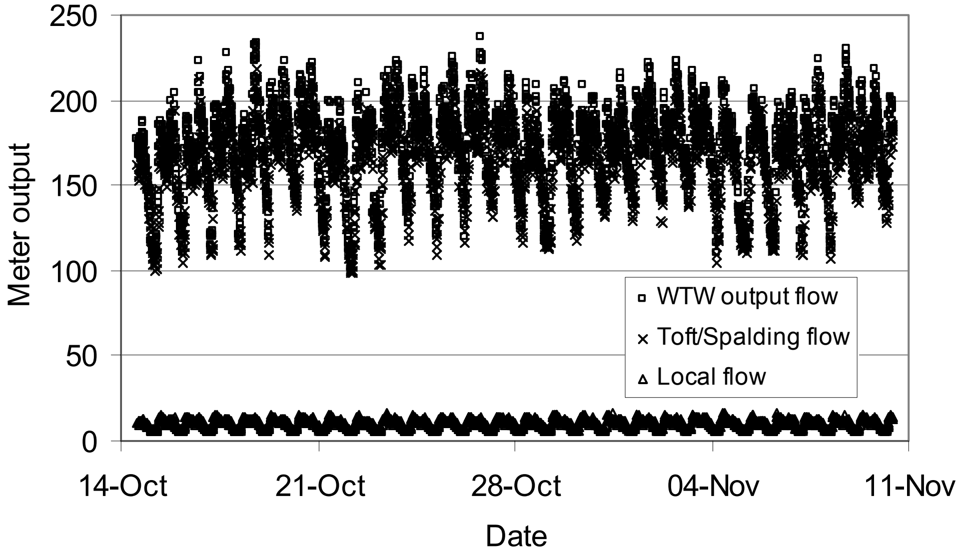


Figure H.16 Raw Data from Bourne Sworps Meters

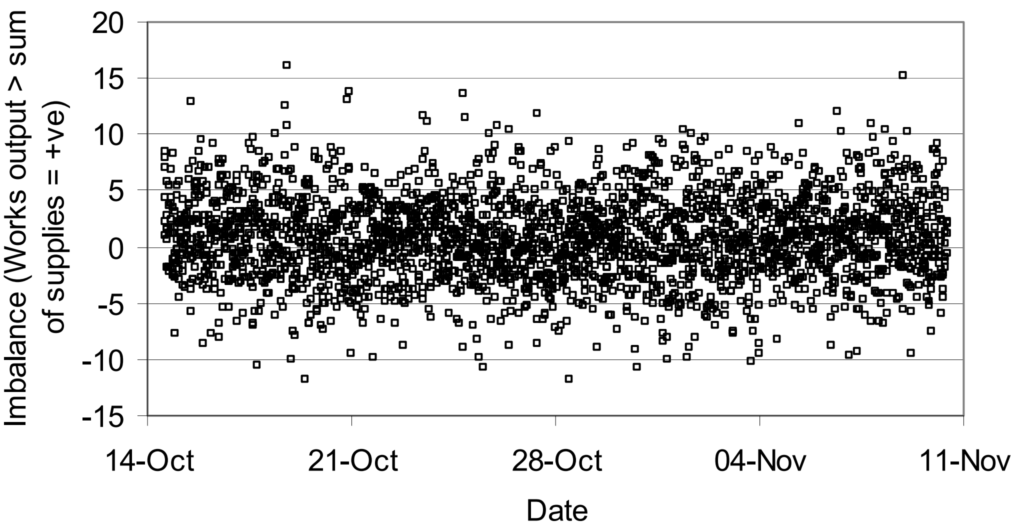


Figure H.17 Imbalance of Bourne Sworps Meters

The signals of Figure H.16 are rather noisy and Figure H.18 shows the daily average flows for each of the meters, together with the imbalance figures. This shows that the imbalance is always very small and that, in general, there is a tendency for the works output meter to over-read when compared with the combined flow to the two individual flows. Although the signals of Figure H.18 show clear weekly cycles for the individual flows the trend in the imbalance figure is much less obvious.

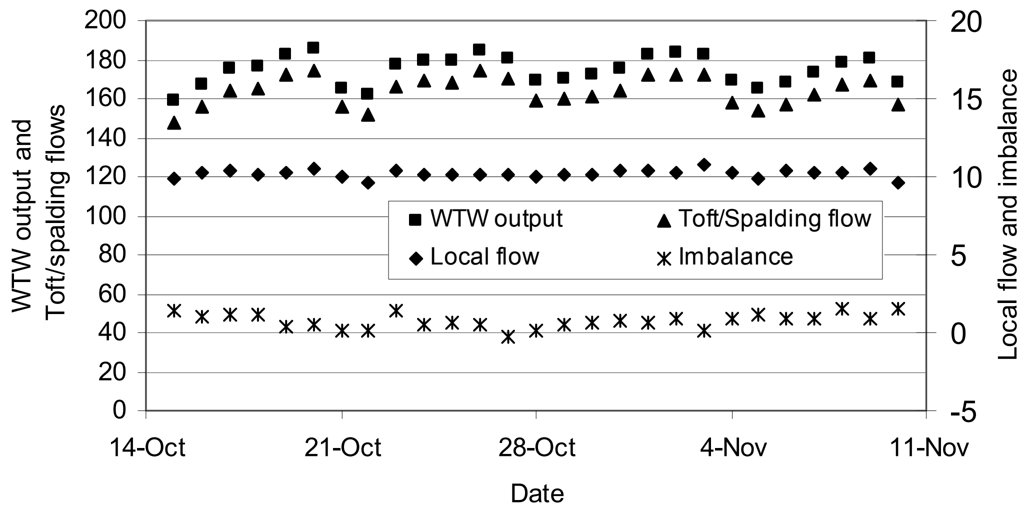


Figure H.18 Daily Average Flows and Imbalance in Bourne Sworps Metering System

(c) System balance

The combination of the two Bourne data files permits an alternative view to be taken. Figure H.19 shows the overall metering set-up and shows that in addition to mass conservation being required on the input and the output, mass must also be conserved across the works, with a suitable allowance made for operational usage on the site. It is then possible to calculate corrections for each of the meters to bring the whole metering system into balance. The presence of storage facilities, such as filter beds, within the treatment works means that it is not possible to perform the balance calculations on a 15-minute cycle and so the analysis was performed using daily average figures, on the assumption that the plant would operate on a 24-hour cycle.

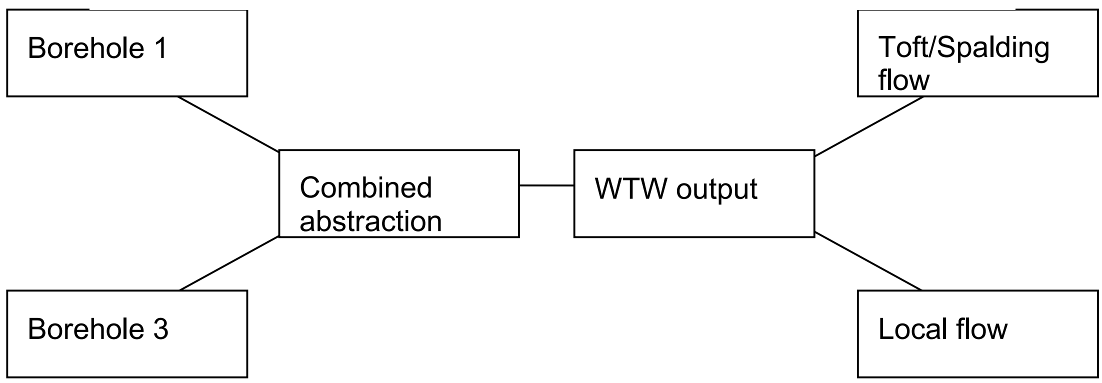


Figure H.19 Schematic of Overall Bourne Metering System

The analysis provides corrections for each of the meters. As there was no information on usage on the site this was left out and should show as a need to reduce the readings on the input side of the works and increase those on the output side. The analysis technique allows the corrections applied to each meter to be biased to allow larger corrections to be applied to meters with greater uncertainty. In this case no information was available for such adjustments and it was assumed that all the meters were subject to the same uncertainty.

Figure H.20 shows the 24-hour averaged signals from each of the meters and shows that over the whole period the combined abstraction meter read lower than the combined (WTW) outlet meter. This points to a calibration fault in one of these meters. Application of the balance equations across the whole network leads to the corrections shown in Figure H.21 as percentages of the individual meter flows. Most of the corrections are less than 2%, with only occasional spikes to higher values; the exceptions being (1) the combined abstraction meter, which required a correction of 4% until the 22 October after which the correction dropped to zero, and (2) the 'borehole 1' meter, where a correction of 7% was required before 20 October after which the requirement fell to zero.

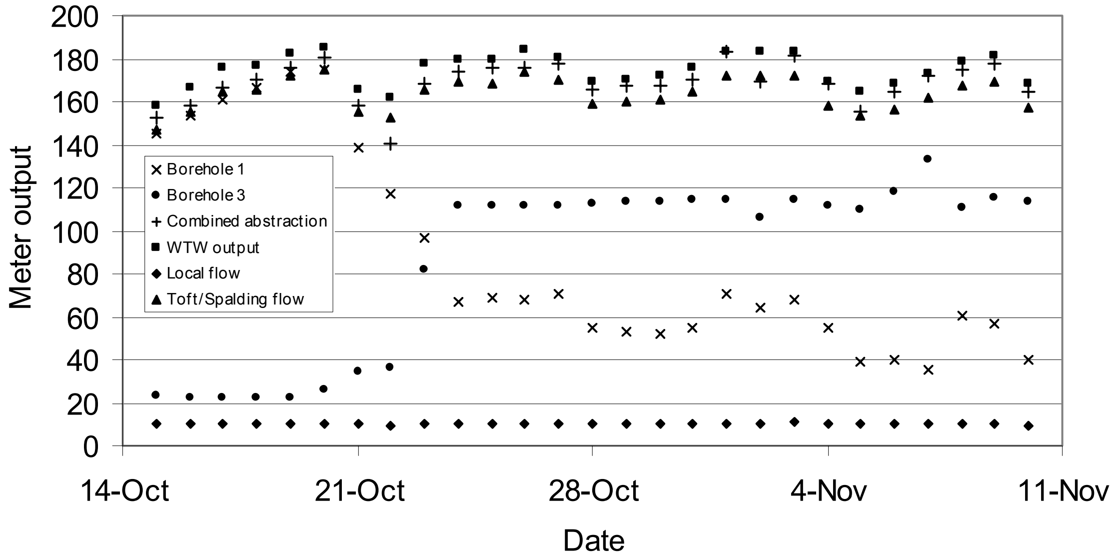


Figure H.20 Daily Average Flows From All Bourne

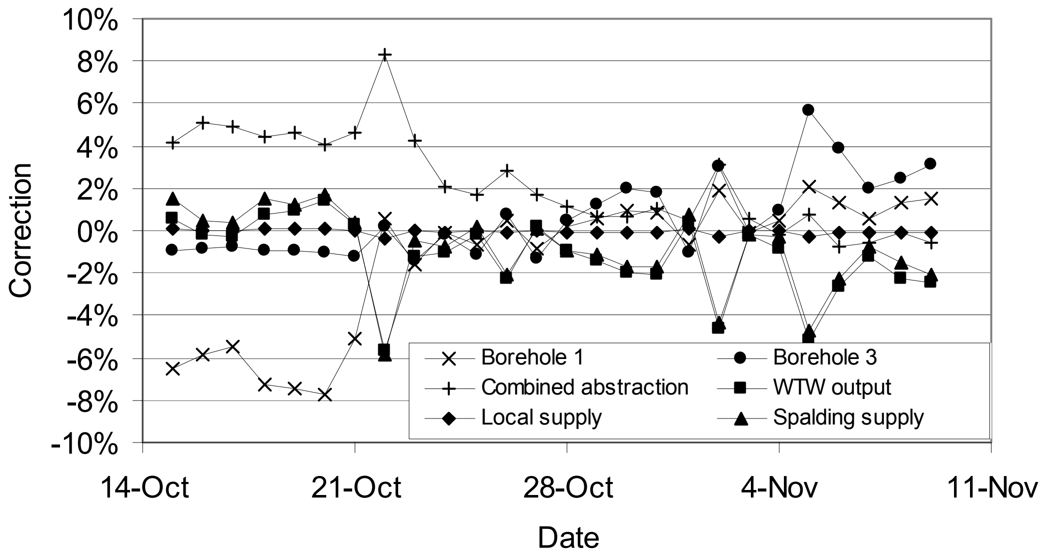


Figure H.21 Balance Corrections as Percentage of Metered Flow

Figure H.22 shows a close-up view of events leading up to 22 October and has been plotted as a control chart (Reference 2). In this view the plotted value is the deviation of each successive day's correction factor from the average correction for that meter divided by the standard deviation of the past corrections. Absolute values of less than 2 standard deviations from the mean value represent random scatter in a system that is running under control and Figure H.22 shows this to be the case until 21 October. Deviations of more than 2 standard deviations represent a warning of a shift in conditions at the 95% confidence level, deviations of more than 3 standard deviations represent a warning of a shift in conditions at the 99.5% confidence level and would be regarded in process control as an alarm level. Figure H.22 shows that all the corrections exceeded this alarm level on 22 October, indicating that something happened in the metered system to cause a serious imbalance at this point. Examination of the earlier plots of the individual meter signals shows that the only significant change in operation at this time was the shift in supply from 'borehole 1' to 'borehole 3'. This again points to a problem in the abstraction metering.

After 22 October all the required meter corrections were, once again, within the 2 standard deviation band except the 'borehole 3' meter which gave alarms levels on 26 and 30 October and on 2 and 5 November. The event on 2 and 5 November were accompanied by spikes in all the other correction requirements. It is difficult to isolate causes for these events.

The individual signals on Figure H.22 should be scattered about the zero line in a stable system, but the correction requirements for the combined abstraction meter is constantly below zero after 22 October, while those for the 'borehole 1' meter are constantly above zero. This indicates that the correction requirements for a balance are drifting with time and Figure H.20 shows that during this period the actual level of abstraction from 'borehole 1' was falling. This may indicate a problem with the meter on this borehole.

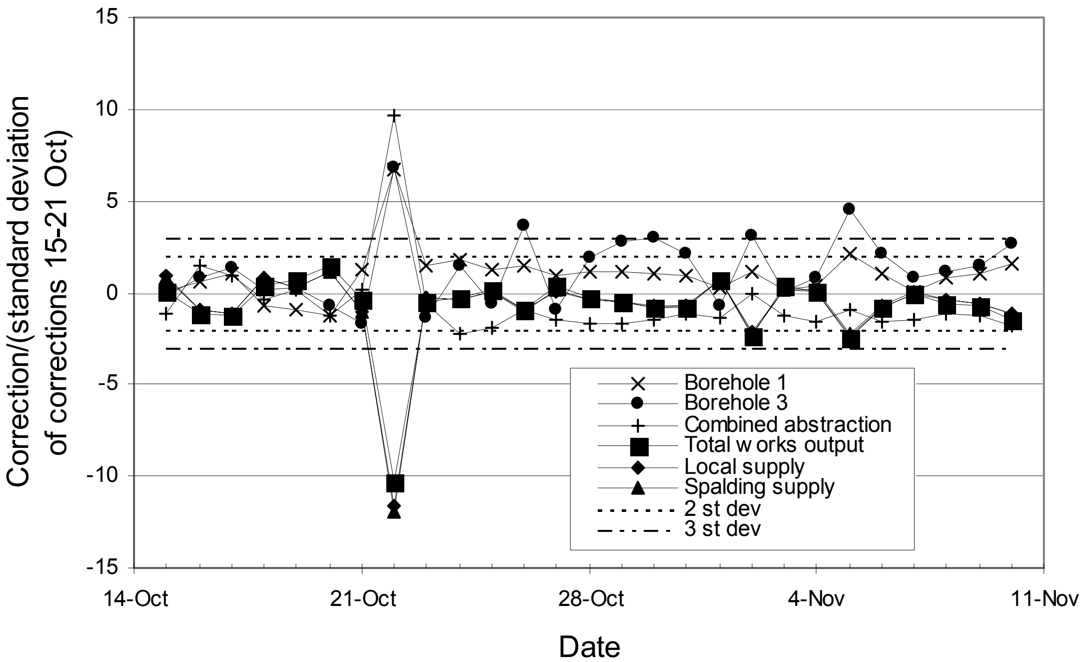


Figure H.22 Control Chart Plot of Corrections in Period 15 to 28 October

In summary the recommendations of this case study are that:

1. independent mass balances on the abstraction and supply sides of the treatment works yielded some interesting results in identifying the relationship between the imbalance and the ratio of the borehole abstraction rates;,
2. a system mass balance across the whole abstraction-supply system yielded much more information, and made it possible to comment on the accuracy of individual meters in the system; and
3. a simple control chart approach to the plotting of the meter corrections required for an overall balance provided immediate warning of the disturbance to the system on 22 October.

H.5 CONCLUSIONS

It has been shown that the application of data analysis techniques can extract a great deal of useful information from the flowmeter data currently collected by the water industry. Three investigations, described in Section H.2 to H.4, have highlighted the benefits of a range of data analysis techniques that could be run automatically as the data were being collected and would result in metering and operational problems being identified more quickly than at present.

One technique which stands out as showing particular potential is the application of Cusums. This statistical method allows changes in mean level in a noisy signal to be highlighted and quantified within a very short timescale.

One set of data studied was shown to be marred by data collection problems relating to the range settings for the computer logging equipment. Recommendations are made to ensure that the flowmeter signals always remain within the range of the logging equipment and that the logging equipment is functioning correctly.

A study of flows at a water treatment works showed that independent mass balances on the abstraction and supply sides could yield some interesting results in identifying the relationship between the imbalance and the ratio of the abstraction rates from different boreholes. However, much more useful information was obtained when a system mass balance across the whole abstraction-supply system was considered. This analysis made it possible for the accuracy of the individual flowmeters in the system to be assessed, and a simple control chart approach to plotting meter corrections was shown to provide an immediate warning of a disturbance in the system.

H.6 REFERENCES

1 BS5703 Part I-IV (1980) Data analysis and quality control using Cusum techniques.

2 Box, G. and Luceño, A. Statistical control by monitoring and feedback adjustment. Wiley Interscience New York, NY. 1997 ISBN 0-471-19046-2